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# Journal

*of*

# THE ROYAL AERONAUTICAL SOCIETY

JUNE 1957

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WITH WHICH IS INCORPORATED THE INSTITUTION OF AERONAUTICAL ENGINEERS

PUBLISHED MONTHLY AT

4 HAMILTON PLACE, LONDON, W.1

*Telephone:* Grosvenor 3515-9 *Telegrams:* Didaskalos, Audley, London

SUBSCRIPTIONS: £7 10s. 0d. PER ANNUM, PLUS 9s. POSTAGE AND PACKING.
SINGLE COPIES: 12s. 6d. PLUS 9d. POSTAGE AND PACKING.

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*None of the papers or paragraphs must be taken as expressing the opinion of the Council of the Royal Aeronautical Society unless otherwise stated.*

PRINTED BY THE LEWES PRESS, WIGHTMAN & CO. LTD., LEWES, SUSSEX, ENGLAND, AND PUBLISHED BY THE ROYAL AERONAUTICAL SOCIETY, 4 HAMILTON PLACE, LONDON, W.1, ENGLAND

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(Founded 1866)

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# *Secretary's News Letter*

*June* 1957.

IN HIS PRESIDENTIAL ADDRESS in January 1956, Mr. N. E. Rowe intimated that the Council had decided to form Sections of the Society.

The Charter of the Royal Aeronautical Society envisaged that the growth of the art and science of Aeronautics would, in due time, involve the creation of Sections of the Society, and included the power to do so. The Council, recognising the current ramifications of the art and the increasing degree of specialisation involved, is of the opinion that the time has come to institute certain Sections of the Society the better to stimulate interest and progress.

Such Sections will be under the general direction of the Council, within the Charter and By-Laws of the Society, but will enjoy a large measure of autonomy in the conduct of their affairs.

The first of these Sections will be

" The Guided Flight Section."

Members of the Society interested in this Section are invited to inform me of their interest, and to register as a Member of the Section.

To enable the Section to begin functioning as soon as possible a Steering Committee has been formed under the Chairmanship of Mr. G. W. H. Gardner. The other members of the Committee are Messrs. H. H. Gardner, M. J. Brennan, R. R. Jamison, H. C. Pritchard and G. G. Roberts.

The Section will be governed in accordance with the following Rules: —

1. The Section shall be called " The Guided Flight Section of the Royal Aeronautical Society."
2. Membership of the Section shall be open to Members of the Society of any grade who shall have notified the Secretary that they wish to be registered in the Section and to receive all notices and publications relevant to that Section.
3. The internal affairs of the Section shall be under the immediate direction of a Section Committee, consisting of not less than seven elected members. In addition one member shall be appointed annually by Council from among their number and one Graduate Member shall be appointed annually by the Committee of the Graduates' and Students' Section.
4. The members of the Section Committee shall be nominated and elected by postal ballot by the registered members of the Section. One third of the elected Section Committee shall retire annually, but retiring members shall be eligible for re-election. The retiring members shall be those with the longest service since their last election.
5. Under special circumstances the Committee may co-opt not more than two members to the Committee; such co-opted members shall have no voting powers.
6. An Annual General Meeting of the Section shall be held on a date agreed with Council.
7. At its first meeting after the Annual General Meeting of the Section, the Committee shall nominate from those of its number who are Fellows or Associate Fellows, one as Chairman and one as Vice-Chairman of the Committee. The Chairman shall, *ex officio*, be a member of Council.
8. It will be the duty of the Section Committee:—
   (*a*) to arrange a lecture programme and to conduct other business, appropriate to the special interests of the Section;
   (*b*) to make recommendations to Council on the normal business of the Society as the Council may from time to time invite.
9. The proceedings of each Section shall be published at the discretion of the Council.
10. Any expenditure to be incurred, or appeal for funds, shall be with the approval of the Council.
11. The Section shall conduct its proceedings within the Charter and By-Laws of the Society.

I shall be pleased to answer any queries regarding Membership of the Guided Flight Section.

A. M. Ballantyne

*Secretary*

# NOTICES

### President of the Society 1957-1958

Sir George Edwards, C.B.E., B.Sc.(Eng.), F.R.Ae.S., President of the Society for the year 1957-1958, took office at the Annual General Meeting of the Society held on 8th May 1957.

### President-Elect

Sir Arnold A. Hall, M.A., F.R.S., F.R.Ae.S., Vice-President of the Society and Technical Director of the Hawker Siddeley Group, has been elected the President-Elect of the Royal Aeronautical Society for 1958-1959. He will take office as President in May 1958.

### Election of Vice-Presidents

The following were elected Vice-Presidents of the Council at their Meeting on the 23rd May 1957:—

P. G. Masefield, M.A., Hon.F.I.A.S., F.R.Ae.S.
E. S. Moult, Ph.D., B.Sc., M.I.Mech.E., F.R.Ae.S.
Air Marshal Sir Owen Jones, K.B.E., C.B., A.F.C., B.A., D.I.C., M.I.Mech.E., F.R.Ae.S.

### Council for 1957-1958

The following are the newly elected Members of Council as a result of the Ballot declared at the Annual General Meeting:—

*Major G. P. Bulman, C.B.E., B.Sc., F.R.Ae.S.
J. R. Cownie, B.Sc.(Eng.), Grad.R.Ae.S.
*Sir William S. Farren, C.B., M.B.E., M.A., F.R.S., M.I.Mech.E., Hon.F.I.A.S., F.R.Ae.S.
G. W. H. Gardner, C.B., C.B.E., B.Sc., F.R.Ae.S.
*P. G. Masefield, M.A., Hon.F.I.A.S., F.RAe.S.
*Dr. E. S. Moult, B.Sc.(Eng.), F.R.Ae.S.
Stewart Scott Hall, C.B., M.Sc., D.I.C., F.C.G.I., F.I.A.S., F.R.Ae.S.

*Re-elected.

### Annual General Meeting

The Annual General Meeting of the Society was held at 4 Hamilton Place, W.1, on 8th May 1957, at which the Annual Report and Balance Sheets of the Royal Aeronautical Society and Aeronautical Trusts Limited for 1956 were approved. The Complete Report and Balance Sheets were published in the April 1957 JOURNAL.

The retiring President, Mr. E. T. Jones, presented certain of the Society's Prizes and Awards to the recipients (a list is published with these Notices).

### School Holidays in France

Following the arrangements made last year, the Society has received names of children of Members of A.F.I.T.A. who would like to exchange holidays with children of a similar age. Full particulars will be sent on application to the Secretary.

### Aviation Psychology

A Western-European Association for Aviation Psychology (Association de l'Europe Occidentale pour la Psychologie Aéronautique) was founded at Scheveningen, the Netherlands on 31st October 1956. The purpose of the Association is to advance the science of psychology, as far as it is related to aviation and to promote a scientific practice of applied psychology in relation to aviation. The temporary steering committee of the Association consists of: J. B. Parry (Great Britain), S. D. Fokkema (The Netherlands), D. J. v. Lennep (The Netherlands), F. Miret y Alsina (Belgium). Membership is open to professionally qualified psychologists employed by Air Forces and Airways Corporations, or performing psychological research on behalf of aviation. Those who do not meet these requirements may be eligible for associate membership. Further information may be obtained from the secretary: S. D. Fokkema, Vossiustraat 56, Amsterdam, Holland.

### Dr. Jerome C. Hunsaker

It is regretted that in the May JOURNAL the citation in the announcement of the award of the Distinguished Service Medal of the N.A.C.A. to Dr. Jerome C. Hunsaker, *Honorary Fellow*, was incorrectly stated. The citation should have read: "for service of fundamental significance to aeronautical science, climaxed by an outstanding and unparalleled record of leadership during the past 15 years. . . ."

Dr. Hunsaker, as members know, retired from the Chairmanship of the N.A.C.A. in October 1956 and is Professor Emeritus of Aeronautical Engineering at Massachusetts Institute of Technology.

### Honorary Fellow

The Council has pleasure in announcing that His Royal Highness Prince Bernhard of the Netherlands has accepted Honorary Fellowship of the Society.

### Honorary Companion

Miss B. Voyce, a former member of the Staff of the Society, has been made an Honorary Companion of the Society.

### New Fellows

The following elections to Fellowship of the Society were announced at the Annual General Meeting on the 8th May 1957:—

George Oswald Anderson
Ronald John Atkinson
Edward Hugh Bateman
Ralph Beasley
Geoffrey Mungo Buxton
Walter Cawood
Geoffrey Dean Dawson
Reginald William Dunn
Leonard Sidney Greenland
Gustaf Gudmundson
Geoffrey William Hall
Ian Malcolm Hamer
Edward Henry Heinemann
Hugh Geoffrey Herrington
Douglas William Holder
Arthur Francis Hutton
Samuel Paul Johnston
James Arthur Kay
Jerome Fox Lederer
John C. Leslie
Sidney Walter Douglas Lockwood
Alfred John Murphy
Alfred Salem Niles
James Norman
Paul Robert Owen
Ronald Charles Pankhurst
James Denning Pearson
Courtland Davis Perkins
Charles Willis Prower
Frederick Gerald Carlton Sandiford
Owen Alfred Saunders
Thomas Ulric Curzon Shirley
Selden Booth Spangler
John Stack
William Arthur Summers
Robert William Symmons

### Medals and Prizes of the Society

The following Awards for papers published by the Society were presented by Mr. E. T. Jones, the retiring President, at the Annual General Meeting of the Society held on the 8th May 1957:—

*The George Taylor (Australia) Gold Medal*, awarded for the most valuable contribution read before, or received by, the Society on Aircraft Design, Manufacture or Operation, to:

Mr. G. Forrest, *Associate Fellow*, and Mr. K. Gunn
(Aluminium Laboratories Ltd., Banbury)

for their paper "Problems Associated with the Production and Use of Wrought Aluminium Alloys" October 1956 JOURNAL.

*The Simms Medal*, awarded for the most valuable contribution read before or received by the Society on any subject allied to Aeronautics, to:

Mr. E. G. Broadbent, *Associate Fellow*
(Royal Aircraft Establishment)

for his paper "Aeroelastic Problems in connection with High Speed Flight" July 1956 JOURNAL.

*The Edward Busk Memorial Prize*, awarded for the most valuable contribution published in one of the Society's Publications on Applied Aerodynamics, to:

Mr. I. M. Davidson, *Associate Fellow*
(National Gas Turbine Establishment)

for his paper "The Jet Flap" January 1956 JOURNAL.

*The Orville Wright Prize*, awarded for the most valuable contribution to "The Aeronautical Quarterly" of the Society on some subject of a technical nature in connection with Aeronautics, to:

Dr. B. S. Stratford
(National Gas Turbine Establishment)

for his papers on the jet flap published in the AERONAUTICAL QUARTERLY February, May, August 1956.

*The Herbert Akroyd Stuart Memorial Prize*, awarded for the most valuable contribution to the Society's publications on Applied Thermodynamics, to:

Dr. J: S. Clarke, *Fellow*
(Jos. Lucas (Gas Turbine Equipment) Ltd.)

for his paper "A Review of some Combustion Problems Associated with the Aero Gas Turbine" April 1956 JOURNAL.

*The Branch Prize*, awarded for the best paper on an Aeronautical subject read before the Branches of the Society and published in the Society's publications, to:

Mr. E. R. Major, *Associate Fellow*
(British European Airways)

for his paper "Some Maintenance Aspects of Viscount Operation" September 1956 JOURNAL.

*The Navigation Prize*, awarded for the best paper on Navigation, including Meteorological Instruments and Test Equipment, published by the Society, to:

Mr. R. A. Burberry
(Standard Telephones and Cables Ltd.)

for his paper "Aerial Systems for Aircraft" February 1956 JOURNAL.

*The Usborne Memorial Prize*, awarded for the best contribution to the Society's Publications written by a Graduate or Student on some subject of a technical nature in connection with Aeronautics, to:

Mr. T. M. Corson, *Graduate*
(British European Airways)

for his paper "The Propeller-Turbine in Airline Service" September 1956 JOURNAL.

## NEWS OF MEMBERS

W. J. AVIS (*Student*) is now employed as a Design Engineer at Convair, California.

Sqdn. Ldr. J. CRANE (*Associate Fellow*) has taken up an R. & D. post in the Royal Radar Establishment, M.O.S., Malvern.

J. H. H. DAVISON (*Associate Fellow*), formerly at A. & A.E.E. Boscombe Down, is now Assistant to the Development Project Officer on the P.1 for the English Electric Company (Aircraft Division).

J. R. FINNIMORE (*Associate Fellow*) who was recently elected an Associate Fellow of the Institute of the Aeronautical Sciences was unfortunately incorrectly described as an *Associate* of the Society in the May JOURNAL. This should of course have read *Associate Fellow*.

T. F. R. GEORGE (*Associate Fellow*), formerly Assistant Chief Technician at Fairey Aviation, has been appointed Head of the Technical Department and Chief Stressman.

A. B. R. HUDSON (*Associate Fellow*), formerly Co-Ordinator of Swift Design at Vickers-Armstrongs (Supermarine) at Hursley, has taken up an appointment as an Engineering Designer at Normalair Ltd., Yeovil.

G. T. KNIGHT (*Associate*), formerly a Senior Design Draughtsman with Saunders-Roe Ltd., has taken a position as Senior Design Engineer with the Lockheed Aircraft Corpn. at Georgia.

F. C. LYNAM (*Fellow*), formerly a Director and General Manager of the Airscrew Company and Jicwood Ltd., has been appointed Managing Director.

J. M. MARSHALL (*Associate Fellow*), formerly at Rolls-Royce, Glasgow, is now working as an assistant to the Quality Control Manager at F. Perkins, Diesel Engine Factory.

F. R. MASON (*Associate Fellow*) is taking up an appointment with de Havilland Aircraft Co. of Canada.

E. B. PEARSON (*Associate Fellow*) is now Associate Professor of Engineering Physics at the Royal Military College of Science, Shrivenham.

J. D. POOLE (*Graduate*), formerly Section Leader of Fairey Aviation Co., has been appointed Chief Aerodynamicist.

G. H. POWELL (*Associate Fellow*), formerly with Dowty Equipment, is now Senior Stressman at de Havillands, Christchurch.

R. V. READ (*Graduate*) has been appointed Engineer-in-Charge, Test Department, Fairey Aviation Co.

Flt. Lt. J. J. C. REID (*Associate*) has taken up an appointment as G.A.I.O. at Air Headquarters, Malta.

J. T. ROBERTS (*Associate*), formerly with Graviner Manufacturing Co., is now Experimental Officer, N.G.T.E., Pyestock, Farnborough.

D. O. SPRATT (*Associate Fellow*) has been appointed Deputy Head of the Technical Department, Fairey Aviation Co. Ltd.

R. G. STANTONE (*Associate Fellow*), formerly with Cummins Engine Co., is now a Design Engineer with the Solar Aircraft Co. of San Diego.

B. R. TEREE (*Associate Fellow*), formerly Chief Engineer and Manager of Engineering and Manufacturing of Greer Hydraulics Inc., has been elected Vice-President in charge of Engineering and Manufacturing.

J. WALTON (*Graduate*) has now completed his research at Imperial College and has joined the Steam Turbine

*Above*: The retiring President, Mr. E. T. Jones, investing Sir George Edwards with the Badge of Office. *Right*: The recipients of the Medals and Prizes presented by Mr. E. T. Jones. From left to right: Mr. Forrest, Mr. Gunn, Mr. Broadbent, Mr. Davidson, Dr. Stratford, Dr. Clarke, Mr. Major, Mr. Burberry and Mr. Corson.

Division of the English Electric Co., Rugby.

Dr. EDWARD P. WARNER (*Honorary Fellow*), who recently retired as President of I.C.A.O., has been elected the first honorary member of the International Society of Aviation Writers.

J. WATKINS (*Associate Fellow*), formerly Head of the Aero-thermo Group at Solar Aircraft Co., has been appointed Chief Analytical Engineer.

G. D. WILSON (*Associate Fellow*), formerly Principal of the Aviation Studies Branch, Australia, is now Consultant of the Personnel Administration Pty. Ltd.

## DIARY

18th-20th July—High Altitude and Satellite Rockets—Symposium. College of Aeronautics, Cranfield.

9th-12th September—Sixth Anglo-American Aeronautical Conference, Folkestone. It is hoped that many members will be accompanied by their wives, who will be most welcome.

15th September—Garden Party, Wisley Aerodrome.

### ELECTIONS

The following is a list of new members and transfers of membership of the Society:—

*Associate Fellows*

Habib Ahmed (*ex-Student*)
Robin John Balmer (*from Graduate*)
Richard Evelyn Donohue Bishop
Jacobus Albert Bosch
Christopher Edwin Burrows (*from Graduate*)
Antony Shiu-Lau Chan (*from Graduate*)
Alan Grenfell Cole (*from Graduate*)
Peter Herbert Cook (*from Graduate*)
Kenneth Leslie Day (*from Graduate*)
Frederick Walter Dee (*from Graduate*)
Patrick Cornelius Donovan (*from Graduate*)
Peter Victor Field
Frank Foster
Keki Rustom Gazder
Leonard Hagger (*ex-Graduate*)
Dennis Alec Head (*from Graduate*)
Michael James Henwood (*from Graduate*)
Harold Edward Holland
Paul Temple Vines Jessop (*from Graduate*)
Alec John Jones
Bernard Cecil Edgar Jones
Francis Edgar Jones
Wolf Kay
Neville George King (*from Graduate*)
Johannes Lie (*from Graduate*)
John Rutter Lloyd (*from Graduate*)
William Henry Lutas
John Dennis Micklem (*from Graduate*)
Robin Middleton (*from Graduate*)
Ian Douglas Neilson (*from Student*)
Stanley Bernard Newport (*from Graduate*)
Ian Howard Grant Nicholson (*from Associate*)
Gerald Victor Page (*from Graduate*)
Alan Middleton Rawlings (*from Graduate*)
Peter Frank Richards (*from Graduate*)
Keith Anthony Rowland (*from Graduate*)
Anthony James Scarr (*from Graduate*)
Ernest Simpson
Cyril William Soley (*from Graduate*)
Kenneth James Staples (*from Student*)
Robert Irvine Taylor (*from Graduate*)
John Thompson (*from Graduate*)
Ernest Alfred Timby (*from Graduate*)
Thomas Thornton (*from Graduate*)
Percy Samuel Victor Vallis (*from Associate*)
Max Dirk Anton Van Olst
James Peter Whitworth (*from Graduate*)
Eric Jeffrey Wightman

*Associates*

John Gerald Beever
John William Bell
Brian John Rollin Boney
Melville Calvert
Bernard Gilbert Carter
Frank Edward Collins (*from Companion*)
Serge Dassault (*from Graduate*)
Reginald William Etchells
Geoffrey Harold Foster
Derek Godfrey Travers Harvey
Moshe Hazan (*from Student*)
Frank Anthony Redvers Higgins
George William Hilless
Alfred Sephton Hughes
Reginald Arthur Johnson
Walter Charles Joiner
John Arthur Lankester
Tom William Mann
Thomas Orpin Maxted
Emilio Alvarez Ojea
John Arthur Padilla
Frank Samuel Preston
Norman Patrick Provins
John Leslie Raine
Roy Arthur Raymond
Ernest Edward Schmidt
Arthur Donald Scott
Daniel Wilson Skillman
Cyril Henry James Spooner
Jeffery Shapcott Whitton

*Graduates*

Cedric George Brown
Gervaise Maurice Geoffrey Cooper
Peter Anthony Douty
Robert Eddy (*from Student*)
Maxwell John Holland (*from Student*)
Brian Horn
John Eric Lightfoot
Douglas Frederick Mann (*from Student*)
James Marshall
David Parkinson Miller
Edwin Mowforth (*from Student*)
David Joseph Payne
George Charles Pearson (*from Student*)
John Cook Scouller
Edward Gunston Tattersall (*from Student*)
Michael Roy Williams (*from Student*)

*Students*

Gangadhar Banerji
Brian Jesse James Bridgeman
Ian Colin Brown
Santi Ranjan Chanda
Paul Victor Cope
Michael James Dean
Prabhakar Makarand Deshpande
George Herbert Dudley Duffett
Norman Arthur Evans
Ian James Foulds
Adrian Neville Gray
Gwyneth Constance Griffiths
David Richard Harris
Michael John Humphris
Denzil Joseph Isaaks
Kenneth Percival
Roger Hugh Moutray Richardson-Bunbury
Davinder Nath Sabharwal
Andrew Joseph Scholes
Reginald Noel Shield
James Craven Waddington
Roger Edgar Whitbread
Edward Bailey White

### NATIONAL ANTI-CORROSION WEEK

A National Anti-Corrosion Week, sponsored by "Corrosion Technology," is to be held from 14th to 19th October 1957. Principal features of the week will be a Corrosion Convention, to be held at Central Hall, Westminster, on 15th and 16th October and a Corrosion Exhibition which is to be held at the Royal Horticultural Society's Old Hall from 15th to 17th October. The main purpose of the National Anti-Corrosion Week is to serve as a focal point for publicity to make industry more corrosion-conscious.

### ACKNOWLEDGMENTS

A number of unusual and interesting historical items have been presented to the Society recently, including a curious memento of the Paris 1878 Exhibition. It takes the form of an ivory furled umbrella four inches long. Through a spy-hole in the handle an aerial view of Paris, with a balloon in the sky, can be seen.

Mrs. D. Harris, of Queen's Gate, London, has given several books which belonged to her late husband. With them was a piece of the propeller from the Halberstadt of Lieutenant Eschwege and a piece of fabric endorsed "Portion of ballonet of bacquet balloon BMS7. Destroyed Wednesday Nov. 21 1917 by Earpig. FINIS." Eschwege gained a reputation on the Western Front for shooting down observation balloons. The British tired of this and sent up a decoy with a dummy observer and a basket of explosive with the detonation operable from the ground. Eschwege shot down one balloon too many but there were protests on both sides as the trap was not considered "cricket."

Mr. R. H. Fairfax, of 13 Randolph Avenue, London, W.9, has presented the following items:—

"Auf den Strassen des Sieges" by Dietrich (an account of the Polish Campaign).

A leaflet (1914) describing a "new" idea for flying machines (J. S. Fairfax).

A leaflet (1940) addressed by the Germans to the Danish Government.

Souvenirs of the Möhne Dam breaching (a link from the protective netting, a German officer's shoulder lanyard, an "iron cross" found in the mud near the Dam).

Souvenir of the visit of King George VI and Queen Elizabeth to Short Brothers factories.

Further presentations, resulting from the notice in the Press, have been received from:—

Mrs. Carey, Kingston-on-Thames.
Mrs. Glanville, Hatfield. N. Skinner, Ilford.

The Council wish to thank sincerely these donors for their generosity.

*The Journal of the Royal Aeronautical Society*

WITH WHICH IS INCORPORATED THE INSTITUTION OF AERONAUTICAL ENGINEERS

VOLUME 61 JUNE 1957 NUMBER 558

# ROBERT HOBART MAYO, O.B.E., M.A., *Fellow*

## 25th September 1890 - 26th February 1957

THE DEATH of Major Robert Hobart Mayo, O.B.E., *Fellow*, on 26th February 1957 at the relatively early age of 66, was a great loss to aviation. It is indeed a privilege to have the opportunity to pay tribute to a man whom I had grown to love and admire, for I had known Bob Mayo for well over forty years and during the greater part of that time I can claim to have known him intimately. He was an energetic and keen pioneer gifted with a quick and fertile brain—but that description alone would hardly do him justice.

To many of us who have been associated closely with the development of flying for a large number of years he seemed to be part of aviation itself, and without his personality and influence things would have been different, and different in a less pleasant way. It was not only his own personal contribution, great as that was, which counted. His infectious enthusiasm, his readiness to listen and be sympathetic to another's point of view, however much off the beam it might at first seem, and his kindly interest, inspired in others an enthusiasm which is, surely, an essential ingredient of success.

Bob Mayo's activities covered a wide field; educated at Perse School and Magdalene College, Cambridge, he was a brilliant student; he was Head of the Experimental Department, Royal Aircraft Factory, in 1914; he saw action in France with the Royal Flying Corps before he became a test pilot at Martlesham and from 1917-19 was Head of the Design (Aeroplane) Section of the Technical Department of the Air Ministry. After the war he became a designer and consultant. As a consulting aeronautical engineer he exerted a considerable influence on commercial flying, particularly on the aircraft operated by Imperial Airways and Instone Air Line between the wars, which culminated finally in the development of the "C" class flying boats with which the former blazed the trail of the Empire routes with such marked success. He was a most active member of the Royal Aeronautical Society, the Air League of the British Empire, the Royal Aero Club and other bodies. He was Chairman of the Air League of the British Empire in 1946 and Vice-President in 1957, Chairman of the Racing Records and Competitions Committee of the Royal Aero Club since 1949, Vice-President of the Federation Aeronautique Internationale and President d'Honneur of the Commission Sportive. He was also a former member of Council of the Institute of Transport.

Probably to many, Bob Mayo was best known for his work for sporting flying; not only British but international sporting flying owes much to him. He officiated at the 1929 Schneider Trophy Race and had served on the Racing, Records and Competitions Committee of the Royal Aero Club since 1934 and represented the Aero Club for many years on the F.A.I. He was one of the most authoritative members of the international Sporting Aviation Commission, serving as Chairman at one time, and was responsible for devising many of the regulations for various aeronautical contests and, also, for introducing a number of important modifications to the Code Sportive of the F.A.I.

*Hay Wrightson*

Major R. H. Mayo.

But others are better equipped to tell of these things. To do so adequately would require the pages of a book

and I must limit myself to a short appreciation of a great man.

Since all the obituary notices I have read make reference to Mayo's connection with the aircraft which bore his name—the Short-Mayo Composite aeroplane—which I, with my co-pilot Harold Piper, had the satisfaction of flight testing, it may be considered fitting for me to tell a little of the inside story of that venture and of our close association in it. To be given the opportunity to do this in the JOURNAL of the Society gives me great pleasure.

Although the trials of the Composite were entirely successful, the process which, for a variety of reasons, took for those days the long time of ten months, was a testing time too for the nerves and tempers of all concerned. Virtually the testing of three prototypes was involved, each component separately, then the two combined, before the real purpose of the exercise, separation in flight, could be attempted. Here it is only fair to interpose that none of the delays was of a major nature but plenty of minor snags and difficulties had to be overcome—they were none-the-less very real ones. Our inability, for a month or two, to start all eight engines, some of which were of an experimental type having to be cranked by hand, in the two hours which tide conditions allowed us each day, was a most irritating experience. Another seemingly insuperable problem at first was to get an "inter-com" telephone that would function in the incredible noise. Then there were a number of indication lights, the purpose of which was to show that the separating forces and trim were in agreement with calculations. For long the lights indicated otherwise, but it was the lights that were in error, not the calculators. During the whole of that period Bob Mayo never showed the slightest sign of impatience, although he must have been on edge at the delay in proving the soundness of his latest idea. Instead, as was so typical of him, he confined himself to quiet encouragement and always dissuaded me from the temptation to take a chance.

Although perhaps the most publicised of Bob's works, to me the Composite was a very small part of his contribution to aviation. But lest it be thought that the idea was moribund from the start or was some sort of publicity stunt with, as things have turned out, only a limited future, I would like to make a few comments.

It may be that we are wiser now, but in 1937 one of the requirements for an airworthiness certificate was the ability to operate from small aerodromes, to "clear the sticks" as we said, in 600 metres. In other words, the designer was forced to design his aeroplane to suit the conditions. Now it would seem the conditions have to be altered to suit the limitations of the design. I suppose it is easier to design an aerodrome than an aeroplane, so this modern policy may be right, provided, of course, that money is available in sufficient quantity. But the fact remains that, using Mayo's idea the world distance record could be (and was) beaten without resource to breaking the, then strictly enforced, take-off regulations or the need for an expensive aerodrome.

The Short-Mayo Composite Aircraft which made its first separation flight in February 1938. The lower component, Maia, was basically an Empire flying boat with a loaded weight of 38,000 lb. and powered by four Bristol Pegasus X engines. The upper component, Mercury, a seaplane, was powered by four Napier-Halford Rapier V engines. In July 1938 Mercury set up a World's Distance record for seaplanes of 5,998 miles by flying from Dundee to Port Nolloth, South Africa, a record which still stands.

That the Composite was a flying boat-seaplane combination was quite immaterial and was so only for convenience. And all this before engines were endowed with fanciful short time powers for take-off and equipped with costly variable pitch propellers which enabled this power to be transformed so efficiently into thrust at the slower speeds.

No, in my view the idea was a perfectly sound one both technically and from an economic standpoint and had not the war been just around the corner, bringing with it a fantastic development of aviation in general, and high speed and heavy aircraft in particular, achieved it must be admitted at an incredible rate by the expenditure of a vast amount of money and effort, I think the Mayo Composite idea would have caught on commercially in a big way.

It is interesting to reflect what impact the jet engine would have had in these circumstances. It might well have been even more momentous.

I greatly miss a very good friend.

JOHN LANKESTER PARKER, *Fellow.*

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*Sir George Dowty,* Hon.F.C.A.I., F.I.A.S., *Fellow*, writes:—

Bob Mayo, by which name he was known to all his personal friends, joined the Society, and was elected to full Fellowship on joining, in 1919.

He served as a Member of Council for a number of years from 1925-1931, 1933-1937, and again from 1943-1947; he was also a member of several of the Society's

Committees of Council over the years and was the Society's representative on the B.S.I. Aircraft Committee for nearly 20 years and on the Segrave Trophy Committee from 1946 until his death. But I make special reference to his splendid work on behalf of the Journal and Publications Committee where for many years we were closely associated. From the inception of this committee in 1944 he was always a keen and enthusiastic member. In the first days of this committee when great changes in the JOURNAL were under consideration—changes that many thought too revolutionary—he gave his full support to those changes and great encouragement to those who were later responsible for carrying out this work. All my colleagues on that committee would agree how much his services were appreciated.

Bob Mayo was unassuming and always kindly and helpful. His sound views and quiet persuasive manner endeared him to all his associates. Many years of co-operation leave me with a lasting impression of his value as a colleague, and leave me too with a happy appreciation of his human side.

His technical achievements were recognised by this Society when in 1939 he was awarded the Silver Medal of the Royal Aeronautical Society, and the citation for this award reads, "For his work leading to an advance in aeronautical design."

In the passing of Major Mayo the Society has lost one of its great members, and his colleagues have lost a good friend who will always be remembered with affection.

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*J. Laurence Pritchard, Hon. Fellow*, writes:—

Major Mayo was a great friend of the Society, serving on its Council and Committees with that regularity of attendance which is often so difficult for voluntary workers on routine and rather dull Minutes. But he never failed to add something to the discussions or proposals. He was an active debater at the Society's lectures, and one who gave a number of significant lectures to the Society as well as to its Branches. He was here, there, and everywhere, at meetings, at formal and informal functions, and travelled widely on behalf of British aviation. His work on behalf of the Royal Aero Club alone would ensure him a niche in the Halls of Aeronautical Fame.

A quietly spoken man, he could hit out hard on occasion. He was very sound technically, and sloppy or ill-considered ideas often brought him to his feet in open debate. Nor was he afraid of attacking those quarters which might have been helpful to him.

On 29th November 1923 he lectured to the Society on "The Development of High Speed Aircraft." In the course of it Mayo intimated that all the world's records for speed and performance of aircraft had settled firmly into the grip of those nations whose technical control was not in the hands of the British Air Ministry. "British Air Policy has been fundamentally wrong since the end of the war," he declared in his paper. "British Air Votes have not compared unfavourably with those of other nations, but the money has gone in every possible direction except those that matter—those of research and experiment." Mayo's attack on the Air Ministry gave a powerful lead to those who spoke in the ensuing discussion, Alec Ogilvie, Mervyn O'Gorman and others, which gave an impulse to the appointment, a year and a half later, of the first Director of Scientific Research at the Air Ministry, Mr. H. E. Wimperis.

When, in 1924, Lt. Col. Fell lectured on Light Aeroplane engine development, Mayo again expressed himself strongly. "I think the one thing which has been clearly demonstrated in the last three years is that the very small aeroplane and engine were quite useless from the practical point of view." In the debate he clashed with Captain Barnwell who believed in smaller engines than the lecturer. Mayo repeated his opinion in a lecture at Ipswich in March 1926. "In my view it is necessary to have at least 60-70 h.p. in order to obtain a reasonably good all-round machine. The latest machine of this type, which has met with considerable success, is the de Havilland Moth."

I often thought that Mayo's real strength was in presenting or arguing a technical case. He marshalled his facts clearly, and stated them shortly, and was not moved by strong and multitudinous opposition. I remember, as many members must, that remarkable and significant lecture given by Dr. Hele-Shaw and T. E. Beacham to the Society in April 1928 on their variable-pitch propeller. Hele-Shaw, who had been Professor of Engineering at Liverpool when Brearey was the Secretary of the Society (and indeed took the Chair at one of Brearey's lectures in the late 1880's) and had lectured on aviation before many of those at this lecture were born, was like a whale among minnows. The discussion was stormy and there were strong undercurrents of feeling. Officialdom was not in favour of the variable-pitch airscrew and talked much about its weight, its cost, its complication, and but little about what its value would be when well developed.

The opener of the discussion, an important figure in the airscrew world, declared "I am certainly not convinced that a strong case could be made for it in heavier-than-air craft .... unless ... one could obtain additional power from the engine of say, 1 h.p. for 2 lb. added weight, it would be better to put the extra weight into the engine and use a fixed pitch airscrew." Other official speakers followed in the same vein. Mayo stood up.

"Some of the criticisms made with regard to the weight were very misleading. Mr. Lynam, for instance, had suggested that for every 2 lb. of extra weight of the propeller one ought to get one extra h.p. and presumably he was basing this on the assumption that the weight of the power plant is as low as 2 lb. per h.p. .... I have no knowledge of any power plant weighing as little as 2 lb. per h.p. .... In order to obtain a true valuation of the merits of a V.P. propeller it is necessary to

consider the weight of the machine as a whole and not merely the weight of the engine ...."

In February 1927 Mayo had lectured to the Society on the Design of Commercial Aircraft from the operational point of view. It was an important paper at the time and drew a first class audience, for Mayo's reputation for talking air sense was high—and deservedly so. He was for many years, indeed, the leading consultant on commercial flying and from those who so wisely accepted his advice I hope that some day proper tribute will be paid to him, a tribute which cannot be fully paid in these present few pages.

There is not space here to quote much of Mayo's sound sense on aircraft design and use, but I think it should go on record that he lectured to the British Association on Trans-Atlantic Air Services in 1939. It was reprinted in the JOURNAL of the Society for that year, and is a first-class sober survey of the position at the time and the difficulties which lay ahead.

But I feel that Bob Mayo's greatest contribution is one which appears almost to have been forgotten. That contribution was one which did more to help the Society, when it was in the doldrums of financial waters, than anything which had happened in its previous long history.

Mayo was appointed European Representative of the Daniel Guggenheim Fund for the Promotion of Aeronautics. This Fund was founded in the twenties, with its headquarters in New York, to help aeronautical education, aeronautical science, and to help those who were concerned with air transport and aeronautical development generally.

It was through the help of Mayo, who at that time was on the Council of the Society and knew its difficulties, that a grant was made of $5,000 in 1926, followed by similar ones in 1927 and 1928, and one of $10,000 in 1929. Mayo greatly assisted me in preparing the letters which would make a successful appeal to the Fund.

On 5th December 1929 I received a formal letter from him about the grants and in this letter he wrote that he had received a letter from Harry Guggenheim, Chairman of the Fund, of which the following was an extract: "I take great pleasure in informing you that a grant of $10,000 was made to the Royal Aeronautical Society in order to enable that distinguished organisation to carry on for an additional two years that part of its work which has been financed in the past by the Fund."

The greater part of the $25,000 grant were used to enlarge the JOURNAL and to carry out the chief function of the Society, the dissemination of technical information.

On 9th December 1929 I wrote a formal letter from the Council to Mayo.

It first of all acknowledged the generous gift from the Fund and continued: "Now that you have returned to England the Council have instructed me to write to you and thank you for the very great efforts which you have always made on behalf of the Society with the Trustees of the Guggenheim Fund. The Council feel that much of the interest which the Trustees have shown in the Society has been due to the able way in which you have presented the Society's case and that it is largely due indeed to your own personal efforts that the Society is now in a position when it can push forward with the many projects which it has had in view during the past few years."

*The Tenth Louis Blériot Lecture*

# Modern Methods of Aircraft Production

by

PAUL BADRÉ

*(President, Société Française d'Entretien et de Réparation de Matériel d'Aviation)*

The Tenth Louis Blériot Lecture was given in London by Colonel Paul Badre on 7th March 1957 at the Institution of Mechanical Engineers, Birdcage Walk, London, S.W.1. Mr. E. T. JONES, President of the Society, presided and welcomed particularly Monsieur Jules Jarry, President of the Association Françaises des Ingénieurs et Téchniciens de l'Aéronautique, and members of the Association who had come from France for the occasion. Introducing the Lecturer, Mr. Jones said:

The Blériot Lecture was founded in honour and memory of Louis Blériot, for so many years a leading figure in French aviation and the first man to cross the English Channel by aeroplane. The Lecture was given in alternate years in Paris and London under the auspices of the Association Françaises des Ingénieurs et Téchniciens de l'Aéronautique and the Royal Aeronautical Society. This, the tenth Lecture of the series, was to be given by a Frenchman of rare distinction. Monsieur Paul Badre was both a test pilot and a technician. Between 1944 and 1946 he was head of the Research and Plans Office of the French Air Force and from 1946 to 1948 he was head of the Flight Test Department of S.N.E.C.M.A. Since 1948 he has been Director of Production at S.N.C.A.S.O., subsequently renamed l'Ouest Aviation, and, to be up-to-date, I believe I should now say Sud Aviation. He is now President of the Société Française d'Entretien et de Réparation de Matériel d'Aviation.

In the course of his career as a pilot in the French Air Force, Colonel Badre had flown 150 different types of aircraft. During the war he directed an information network in radio communication with London until, in 1942, he escaped to North Africa and once again became an operational pilot. His outstanding record of service earned him the distinction of Commander of the Legion of Honour. They were fortunate in having as their lecturer that evening a man of wide aeronautical experience and sound judgment.

## Introduction

THE subject of aircraft production is obviously a very wide one—books have already been written on it—books which have been consulted when preparing this lecture. It is proposed to sketch in broad outline the various methods generally known for the manufacture of aircraft, dwelling perhaps more particularly on some with which I am more familiar and which have recently been used very successfully in French factories. Familiar processes which have been in use from the earliest stages of aviation development up to recent years will not be discussed, but an attempt will be made to bring out the salient particular features of the new processes and the new production methods which seem to offer interest not only from the historical, but also from the technical, aspect at the same time indicating the extent to which aircraft engineers have had to exercise their ingenuity in order to build and mass produce aircraft which are being constantly developed and improved by the Design Offices in different countries.

Starting from very complete detailed drawings meticulously prepared in the Design Office, the series production of aircraft consists in producing aircraft made up of assemblies, sub-assemblies and component parts of equipment, all identical in manufacture, each part, each sub-assembly and each assembly being easily replaceable by the user or a person undertaking repairs, by parts, components and sub-assemblies already manufactured on the same machines. For this purpose, remembering the complex character of the aircraft at present being designed and manufactured and the high performances demanded of the aircraft, as well as of the constituent materials, it is essential to apply the most advanced engineering methods available to industry. Until the past few years and particularly before the jet age, this was not always the case, since the raw materials used, in the form of fairly thin sheet metal and steel in small quantities, the level of performance and the comparative simplicity of shape achieved, were such that repairs and replacements of parts could be made with required fits by an operator doubtless skilled but with loosely defined responsibility. Nowadays, when aircraft are made of thick sheet metal, with high duty steel or light alloy forgings, and in complicated shapes, this can no longer be the case. We must, in fact, proceed in the same manner as in the car industry, where any part bought in a shop must be capable of being fitted on any car without the necessity of special fitting. We, however, are confronted by the further problem that in our case manufacturing and machine tolerances are much higher. This means that the machine tools must be particularly rigid, the stamping machines must be particularly well made, the assembly jigs must remain rigid and carefully aligned, while the equipment assemblies must be prepared in detail and with the utmost completeness.

In order to study more fully the problem of aircraft manufacture the various operations entailed in the series production of a modern type of aircraft, that is,

one capable of high performance, will be dealt with in some detail. Particular stress will be laid on processes which are perhaps less familiar but which appear to have a very promising future. The starting point is, of course, in the Design Office with the compilation of a complete and detailed file of working drawings and instructions. This file must take into account the production potentialities and be drawn up in close collaboration with the engineers acquainted with the methods used in the factories which are to make the aircraft. Working from this basis, the manufacturing firm transfers on to full-scale metal sheets the various drawings relating to the shape, and the different sections of the equipment to be manufactured. The methods for doing this are well established, ranging from ordinary engraving with a scriber to sundry lithographic, or photographic, processes which will not be elaborated. These drawings enable the decision to be taken, on the one hand, on what machine tools are required for the manufacture of the mechanical parts, that is, those parts which are produced from metal by removal of chips and, on the other hand, the stamping tools needed for making the skin or frames of fairly complex shape by deformation of the sheet metal and exceeding its elastic limit. Finally, there are the fitting adjustments and the assembly jigs on which all the component parts of an aircraft, like those of a huge jig-saw puzzle, will eventually be assembled. In addition, there will be jigs for making the auxiliary equipment, including the pipes, electric wiring and various instruments to be fitted inside the framework, as well as the test rigs for checking the working of the different types of equipment as they are installed. When finally completed, the aircraft leaves the factory, undergoes a number of ground tests and is then flown, tested, touched up if necessary, and delivered to the prospective user.

Consider first the methods used for producing mechanical parts, starting from forgings or stampings. Parts cut from the solid are worth while only in the case of prototypes or very small series which have to be completed quickly, or when the necessary means for forging or stamping are beyond the capacity of the industry. It is natural to find the largest forged components (produced directly by forging), *e.g.* the wing spar of the F.102 Convair, in America, where there are forging presses of up to 50,000 tons. Another instance justifying the use of parts machined from the solid is familiar to everybody. It occurs at the beginning of a series, or when a considerable modification is being made and the dies called for in the drawing cannot be supplied in time as a result of the period spent in tool making.

Copying milling machines have been in standard use for an appreciable time in the engine industry and have proved particularly advantageous in the production of turbo-jets, where a large number of fairly small parts are machined into identical shapes with close tolerances. In the production of airframes, it is only in recent years that these machines have come into current use, the majority of them, at any rate in Europe, being still equipped with hydraulically operated copying devices. (Fig. 1). Such devices operate chiefly by means of wooden models which guide the feeler, the movement of the latter being accurately copied by the tool holder spindle, which is generally small, of course, for components of complicated shape. There are, however, many different types of copying milling machines, the simplest being the profiling machines which have become a speciality in England and in which the operator simply guides the feeler by hand. This does not, however, prevent the operational head from possessing a considerable power which may reach and even exceed 10 h.p. In this case, copying is obviously uni-dimensional, that is, a matter of contouring. Copying, however, is of great value, particularly for rectilinear components in which the cross sections of the forms are determined, that is, generated by straight lines moving parallel to each other. For small or medium sized parts of complicated shape it is often economically practicable, after the first piece has been produced on a manually guided milling machine by skilled operators to use the first piece,

FIGURE 1.

or pieces produced, as a template and to perform the rest of the work by automatic means. An interesting example of this is the mounting of the Caravelle jet engine, a large steel component of complex form in current production on a large copying milling machine.

The incorporation in modern aircraft of mechanical parts with shapes of increasing complexity and variety has led to a great increase in the use of copying milling machines. There are two special fields in which these machines can be used with advantage: one is the machining of large wing spar extrusions, where the machining is performed on special very large table machines which have been in use in America since the last war and are used in Europe by the majority of large aircraft manufacturing firms. These machines operate with a moving table and fixed spindle, or with a fixed table and moving spindle. The design of the first machines produced was definitely based on the technique of wood-working machines and they are, in fact, more like spindle moulding machines than milling machines (Fig. 2). They are well known and in use everywhere to some extent. They possess the great advantage of reducing, frequently to less than one-tenth, the time which would otherwise be required for manufacture, if more conventional means were used. Another type of machine which has appeared quite recently, first in America, then in England and now in France, is the machine for milling the skin coverings (Fig. 3).

It has been realised for some time that the fewer the different parts making up an assembly, the lighter it is for equal strength. It is therefore advantageous (from the strictly theoretical point of view, of course) to start with thick light alloy or steel slabs and to scoop the form out of the solid; this is better than starting with sheets of constant thickness or tapering thickness and, to give them sufficient local rigidity and moment of inertia, to assemble on these longitudinal and transverse stiffeners of more or less complicated shapes which are themselves machined separately and assembled by riveting, bolting, welding or gluing. Starting with a thick slab and actually scooping it out of the solid, it is clear that, as regards the uniformity of the whole, the result is much more satisfactory than a structure which has been assembled, even in the case of gluing. The reason for this is that the joints do not merely occur at intervals, but over the whole length of the profiles concerned. Machines for this process, however, could only be used when metal manufacturers were able to supply big enough ingots to enable the required parts to be produced from them.

It must be remembered that one commonly finds the original block of raw material reduced to one-tenth of its initial weight by the end of the machining operation. The next step was to perfect the high power motors which are used so that the work shall not take too long to perform. Last, but not least, it was necessary to complete all the ancillary equipment in these machines. This ancillary equipment ranges from the generally very complicated electrical supply system and the various hydraulic or electronic copying devices, to the carrying away of the chips, since a machine of this kind is liable to become buried under its own chips, even in 24 hours, if they are not removed. Devices for conveying away the chips, for removing them by means of a liquid, or by roller-tracks, etc., were required and had to be designed before the machines could be put into general use. Lastly it was necessary to decide upon and to develop the most suitable devices for fixing the ingot on the table of the machine, such fixing being achieved either by a vacuum,

FIGURE 2.

FIGURE 3.

when using light alloy, or magnetically in the case of ferrous metals.

A final point is that these machines, like the machines for milling spars, have to be provided with means for straightening on a large scale. It is essential to have such means, since the machining operation, which cannot of course be symmetrical, always produces considerable stresses in the components, even after intermediate heat treatment. The form of the components as they leave the machine is quite unlike that which they must finally assume. Thus presses or bull-dozers are needed for straightening them—faceplates for checking purposes and possibly intermediate heat treatments in order to give stabilisation. Consideration has even been given to the use of quenching under pressure in special presses to overcome this difficulty. An interesting device in this connection is the stamping device on a bed of metal balls, which is sometimes used in America.

In the light of these difficulties, the machining of such complex shapes obviously presents problems as regards the purchase of very expensive equipment—the smallest machine for milling skins costs about 90 to 100,000 American dollars—and several countries have hit on the idea of using, particularly for light alloys, a method for removing metal based on quite a different principle. This is the so-called chemical machining, which consists of masking on a panel by some process such as gluing of an adhesive, special paper or waterproof cloth, the parts which have to be kept and retained, and applying over the whole surface for a given time a corrosive liquid, which is generally caustic soda for light alloys or an acid for steel. This produces directly in the metal all the hollows required by the design (Fig. 4).

This process has been successfully applied to relatively thin panels where mechanical machining is a particularly delicate operation, but it cannot yet be

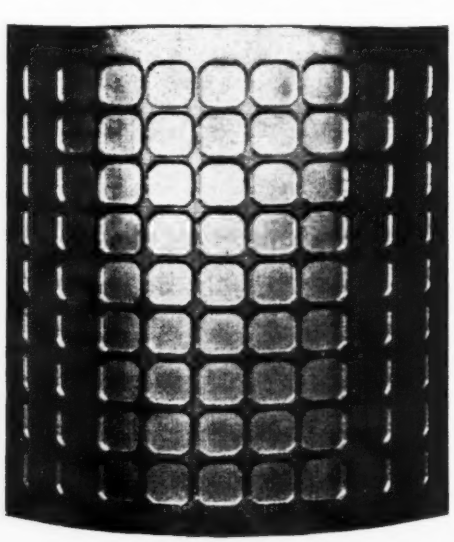


FIGURE 4. Chemical machining of a component with square stiffeners.

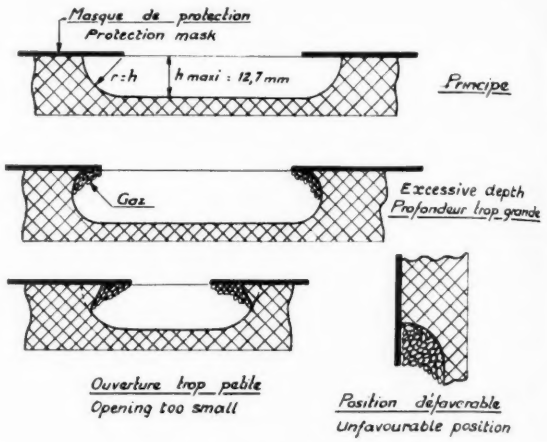



FIGURE 5.

used, it seems, for thicker panels because of the large number of bubbles which occur in the corners and restrict the effectiveness of the process (Fig. 5). It is, however, a process which appears to have great possibilities and it is not expensive. The tanks for the immersion of the parts and the treatment involved cost much less than the huge machine at present used for the mechanical removal of chips. It has, too, another very important advantage; it does not cause additional stresses as a result of the action of the tool, and the shape of the components, once machined, is very nearly that of their final shape which they may even have assumed previously by a conventional method of forming. To some extent, therefore, the large presses for straightening and re-forming required in the previous case may be dispensed with.

There has been much talk recently, in connection with the production of mechanical assemblies, about what is known as automation. It was mainly the motor car and electrical industries which aroused the now almost universal interest being shown in this new technique. In the production of aircraft, automation has so far only been used somewhat sporadically, but this does not mean that it is not capable of considerable development. We are already making use of automation by having copying milling machines which can be handled by an ordinary skilled operator and which automatically produce the most complicated parts. Another example of automation is the use in high power hydraulic presses of automatic feed devices and revolving tables which enable a large number of parts to pass one by one under the ram of the press, with the minimum of difficulty in handling for the attendant operator.

There is another method which appears to be relevant and to resemble automation as practised, for example, in the motor car industry. We are all familiar with what are known as transfer machines, that is, working head assemblies arranged in a fixed position at various working points in front of which the component to be machined passes to be successively milled, drilled, reamed and perhaps rectified. The movement

from one position to another is usually effected automatically. In the field of aviation, as far as relatively small components are concerned, some progress was made in the use of transfer machines. The machines designed, for instance, for the production of control rods, which are more or less standard aircraft components and for the manufacture of stampings, have definite fixed working positions to which the various components to be machined move, generally without the necessity of devices for automatic handling. A knuckle joint, for example, will be successively turned, milled, drilled, reamed and threaded. A sequence of four operations is thus quickly completed, the movement from one operation to another being effected manually.

Automatic handling devices are extremely costly and their purchase is not justified for aircraft production where the number of parts to be made is always limited.

Another interesting trend in a neighbouring field should also be mentioned. Large units such as fuselages and wings are often joined together by means of multiple joints, large forged or machined brackets with a large number of holes through which pass special steel bolts made to extremely close tolerances as regards diameters, distance between centres and parallelism of the contacting surfaces. No purpose is served by adhering to these tolerances in the case of the fixing pieces themselves before their inclusion in the structure, since the latter is usually made up of sheet metal assemblies where the manufacturing tolerances however reduced they may be, are not comparable with those required and currently obtained in the case of the mechanical parts. The method now currently used in this connection is to perform finishing machining, that is, the operations giving the final tolerances, on the piece only after it has been placed in position for the assembly of the structure. In this case, the milling, facing and reaming heads required should be fitted on fairly large frames so that the particular wing or fuselage section, for example, can be set up in the machine in one whole piece (Fig. 6). A further advantage is that of perfect interchangeability not only between the joints, but, what is more important, between the components to be joined. We then know, for instance, that any wing can be fixed to any fuselage (Fig. 7).

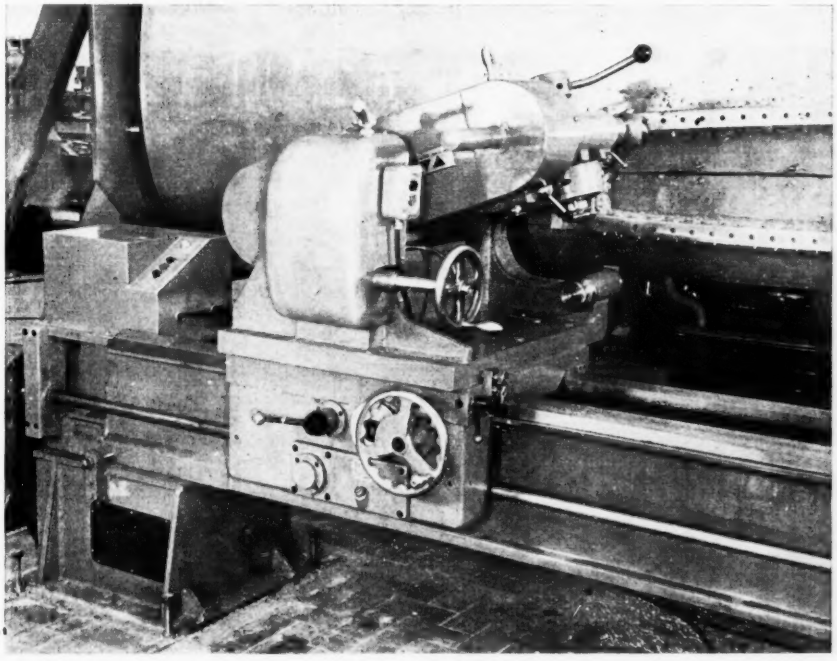


FIGURE 6.

A variant of this method is to cut out directly on already finished or stiffened panels, even on completed fuselages, openings for doors or escape hatches of more or less complicated form, which are made in adjoining workshps or in sub-contractors' works.

The complicated forms are made by deformation of sheet metal or profiled components, such deformation being performed by applying either an almost normal pressure of from 150-400 kg./cm.$^2$ (2,135-5,690 lb./in.$^2$), or a tensile stress which causes the elastic limit to be exceeded but does not, of course, bring about rupture. The tensile stress is obtained by means of jaws connected to suitably articulated jacks and applied to the ends of the panel (Fig. 8). In the first case, the pressure is applied either by compressing the part between a punch and a die, or, alternatively, by pressing the part against a punch by means of some liquid or plastic material such as rubber. The rubber is placed in a container to prevent its escaping outside and to create an almost uniform pressure over the whole part.

Many different types of flanging presses have been made and are familiar to everyone, but the Verson Wheelon type of presses which have appeared fairly recently on the market should be mentioned. These presses were developed in America and enable extremely high pressures to be obtained without the bulk and the weight of the usual type of flanging presses.

Forming by drawing has been considerably developed during the past few years, particularly for the skin panels where the curvature, although relatively slight, may assume fairly complicated forms which are neither capable of being made into, nor do they correspond to, conventional geometrical shapes. The

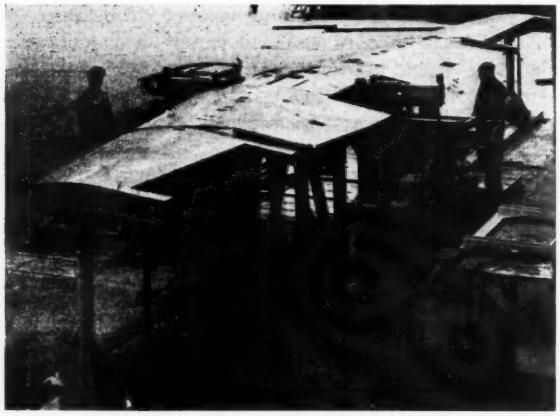


FIGURE 7.

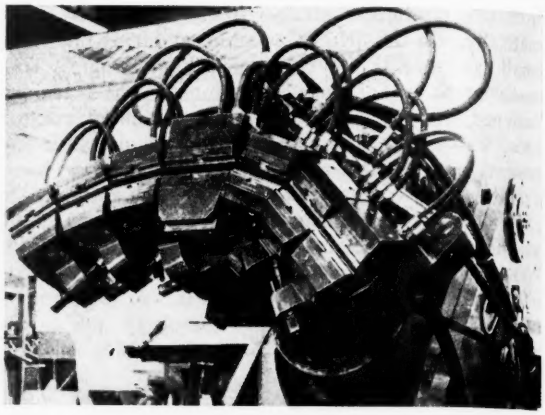


FIGURE 8. 100 ton machine. Working head with hinged jaws.

machines for forming by drawing are the Hufford Sheridan type, S.N.C.A.S.O. (Fig. 9).

At this point it will be of interest to discuss the actual construction of the tools and to see how, from the relevant drawings, it is possible, without great difficulty, to produce tools enabling us to build up accurately the whole mosaic pattern as it were, of the assembly of an aircraft comprising several thousand, and sometimes several tens of thousand, different parts. A fairly well-known method is to start from drawings of sections of a component and, by means of these sections, to make a full scale plaster model of the component. For a fuselage, for example, the frames are traced directly on the metal and, after being cut, serve, together with very light struts, to represent a skeleton. The spaces in this frame are filled with some patching material, such as wire gauze, stuffing, even straw incorporated with plaster sometimes bound with resin. The surface is made perfectly smooth so that a fuselage exactly similar to the final version can be constructed (Fig. 10). An improvement on this method (Fig. 11) is to trace directly on this fuselage with a scriber, for instance, all the intersections and all the fixing joints of given components, including wings, tail units and supports for various equipment. This can be done with any desired degree of accuracy (Fig. 12) and reproduction can then be performed in the following way.

When the fuselage frame has been constructed, hollow moulds are cast over it, using suitable fittings. When removed, these moulds which are made of plastic, produce moulds into which the thermosetting plastic substance can be immediately poured, finally enabling the press tool to be made. The thickness of the metal sheet is taken into consideration during this casting process by a suitable decrease in the thickness of the model, or by the use of suitable sheets of lead. By applying a coat of what is called a separator, that is, a very thin film of a special product, the resin is kept from sticking to the plaster and the line marked on the model by the point of the scriber can be made to stand out on the mould (Fig. 13). Two things can be obtained by this method: either the tool for flanging or drawing in a form which makes it possible to reproduce the component to be fitted in the final assembly, or some basis for the assembly jig on which will

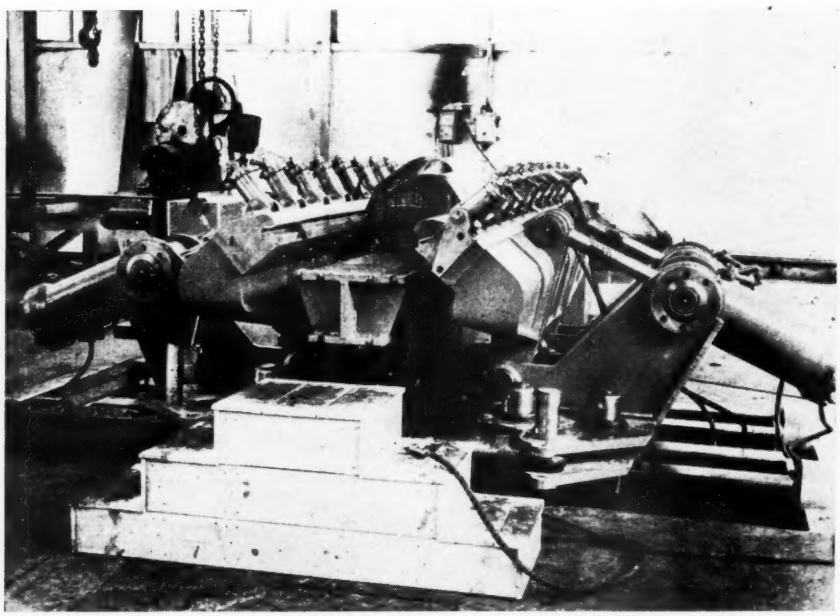


FIGURE 9. 150 ton machine for draw-forming. Forward part at end of operation.

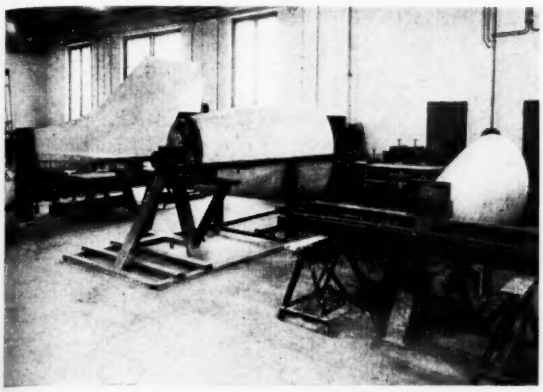


FIGURE 10.

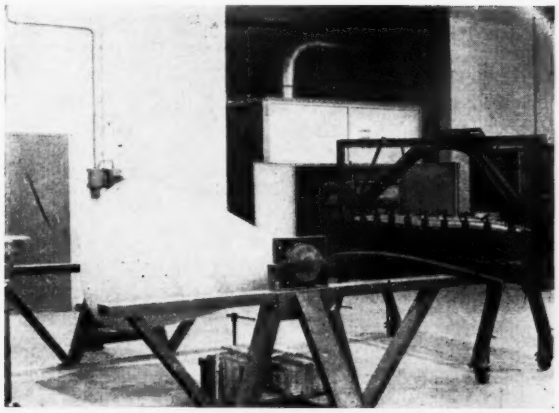


FIGURE 11.

be fitted, without any possibility of error, as a result of the copying of the drawing, the various supports, frames and different components making up the aircraft structure.

The general use of this method can even be visualised. For a spar in a structure which has to be fitted with any arbitrary relative form into some part of the structure, there is no reason why a plaster model of the spar (Fig. 14) should not be built on the hollow form already obtained and from this model the pressing tool is cast (Fig. 15) for making the spar (Fig. 16). The fuselage spar of the Vautour aircraft provides a good illustration of this process (Fig. 17).

It is possible by this method to take directly from the model the tooling required for the manufacture of components of the most complicated shapes. The Vautour spar was made on a very large bending machine in the St. Nazaire works of the Société Ouest Aviation (Fig. 18). The use of more conventional methods would have demanded tools which would probably have taken several months to produce and several weeks to perfect.

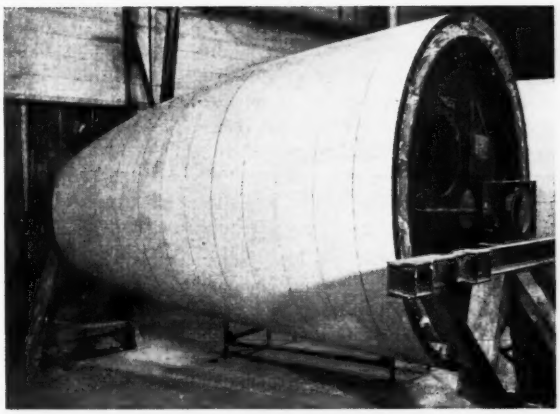


FIGURE 12.

This simple method of reproduction by casting from a model enabled us to produce the tools in a little under a fortnight and proved entirely satisfactory. It should be mentioned—and this English audience will probably be the first to appreciate the fact—that methods of assembly during the past few years have undergone a marked development, in which the Fairey Aviation Company have played no small part by perfecting their equipment for starting assembly

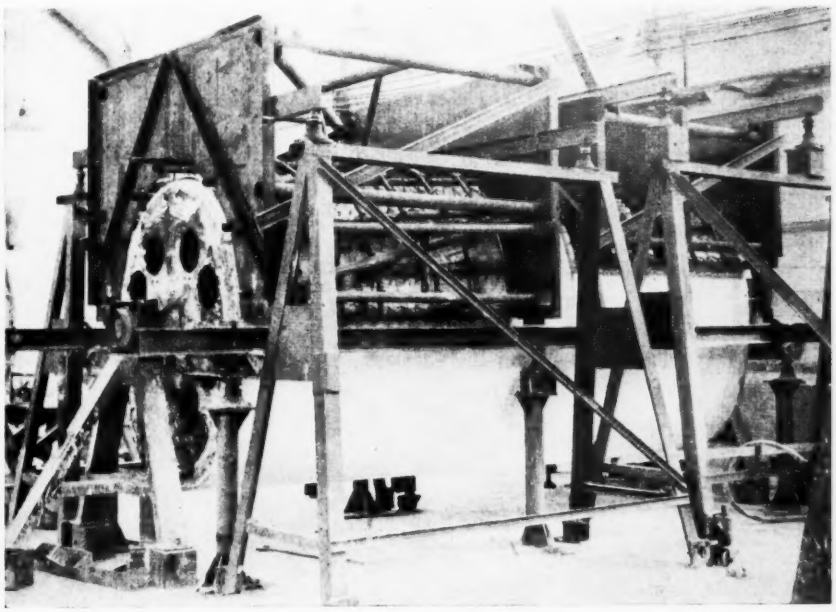


FIGURE 13.

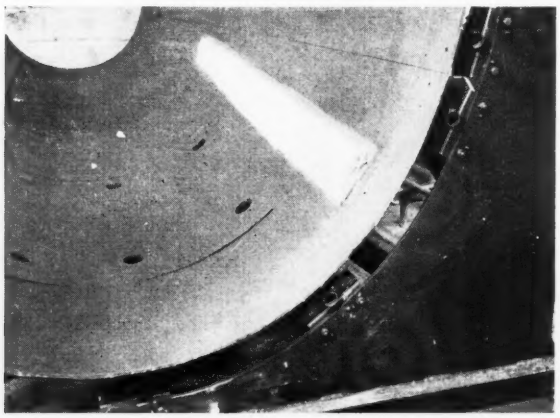


FIGURE 14.

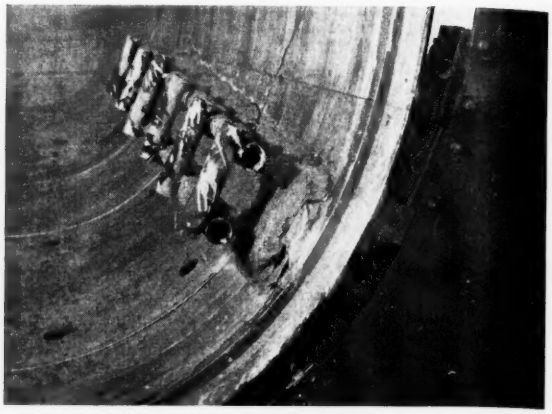


FIGURE 15.

work from the outside. Up to the past few years assembly was always begun by setting up the skeleton of the unit to be made (Fig. 19) and then applying the skin to this skeleton. This operation, which was not accomplished without a great deal of difficulty, caused deformations and buckling to occur which often gave the structure the appearance of a somewhat thin body with protruding ribs. The Fairey Aviation Company were the first to conceive the idea of equipment which started the work of construction from the outside instead of from the inside. The skin, already provided with its various stiffeners, thus becomes the basic component on which the various pieces of the skeleton are fixed. The result, when assembled, is a perfectly smooth unit, with no deformations or internal stresses.

The method used by Fairey's consists in making jigs having the exact shape of the skin and marking on the surface the various points for attachments and drilling which enable the skin panels and stiffeners to be fixed in place.

A variant of this method, now in use in France, is to have plastic counter-moulds for the outside walls of this jig, generally made of epoxy resins with various additives, on which will be fixed the attachment points of the other components of the structure (Fig. 20). These epoxy resin counter-moulds are obtained directly from the models mentioned earlier, so that these models are used not only to make the tools for the main plating parts but also for their assembly on the assembly jigs. The advantage of this process is immediately apparent. Since both the components and their assembly jig come from the master model, no difficulty arises in the assembly, the tooling is adjusted right from the beginning and the parts fit well from the start in the jigs and assemblies of which they are to form part. Experience with this process (Fig. 21) was obtained in France in the first place on aircraft components, in particular with the rear fuselage of the MD.Mystere IV and it has been general in the case of the Vautour production, where almost every part of the aircraft was made according to this method (Fig. 22).

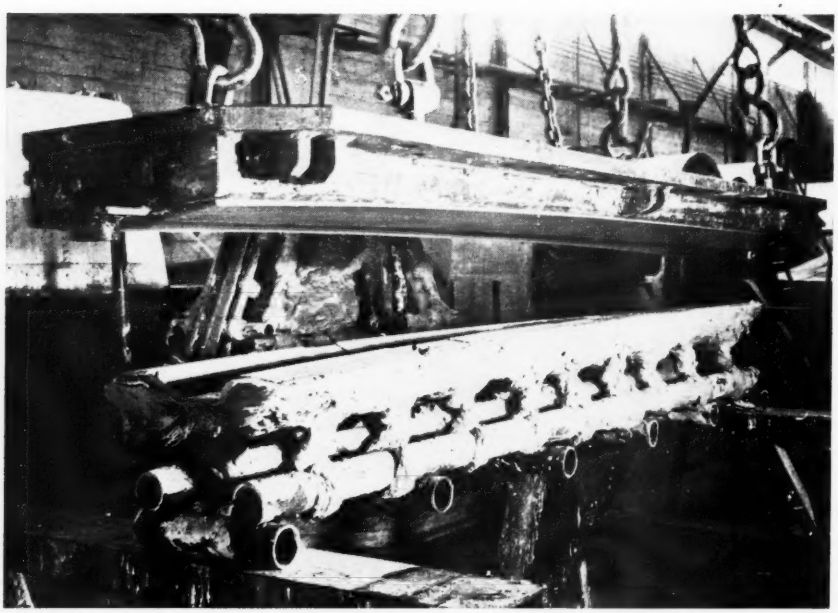


FIGURE 16.

It is worthy of note that the chief justification of the method is that the first production aircraft was fitted and assembled as easily as the 10th, 15th or 20th aircraft. Practically no modifications had to be made to the tooling, a fact which in the author's opinion is of extreme

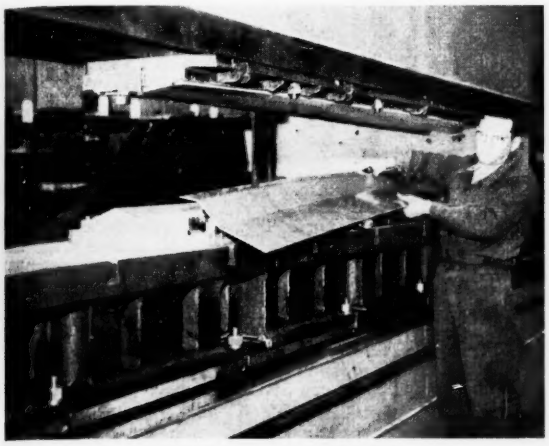


FIGURE 17. Fuselage spar of the Vautour.

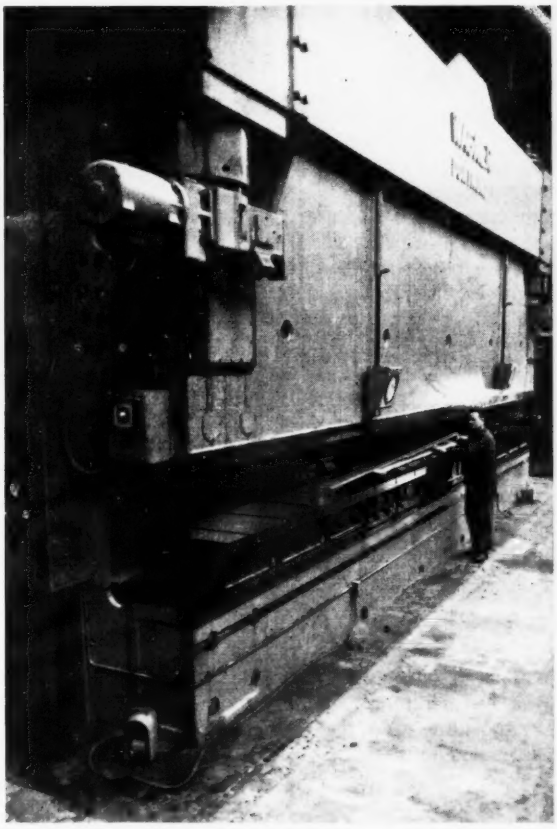


FIGURE 18.

importance and largely justifies the small complication at the beginning of this process, necessitating, as it does, the manufacture of very large plastic components with fairly precise tolerances. The trouble taken at that stage is largely compensated by the ease with which even a complicated unit, like the Vautour, for example, is assembled and takes shape in the assembly jigs.

After completion of the assembly comes the installation in the aircraft of all the necessary equipment, that is, all the pipes, ducts, flight instruments, in a word, everything which will make the aircraft serviceable. Here, too, a variety of methods may be employed. The easiest method for the beginning of a series is clearly to complete the framework first of all, then to place in position inside the airframe the various supports for the equipment, and finally, to install the ancillary equipment itself. This is the process used for the manufacture of prototypes or very small series. The method cannot be applied for larger series since in present day aircraft the ancillary equipment is very often situated in positions where it is difficult to have a large number of fitters working. Over and above this, particularly skilled men are required for this type of work. The present tendency, which has in fact been in evidence now for a number of years, is to produce separately the various types of equipment sub-assemblies, systems of pipes

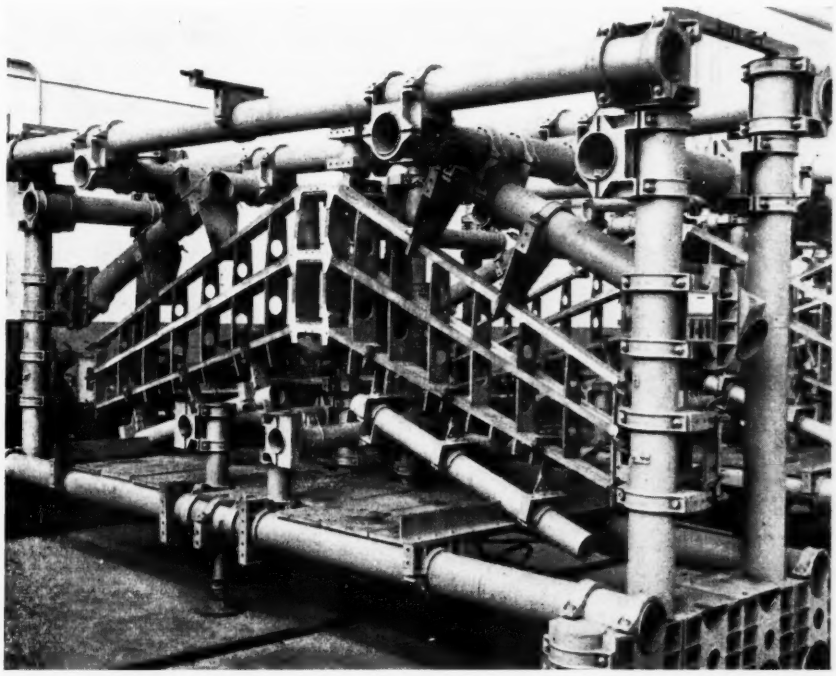
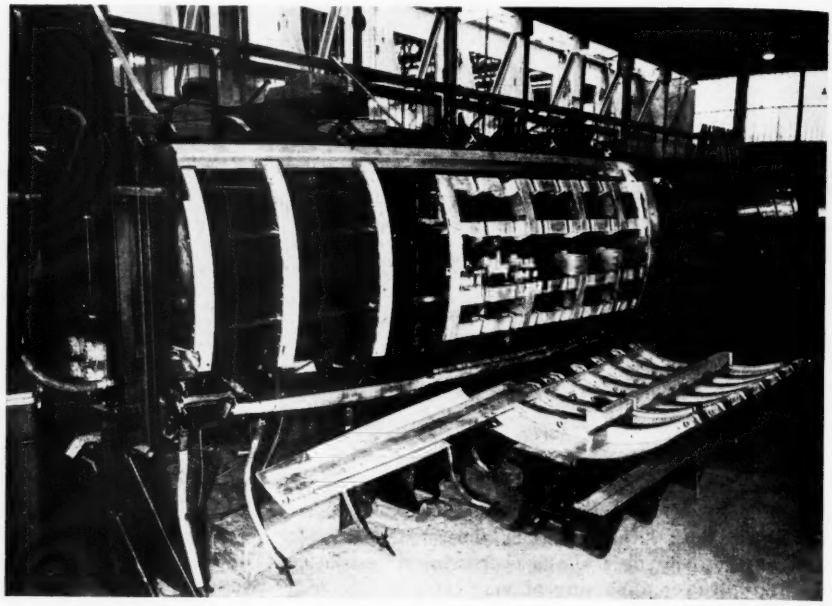


FIGURE 19.

FIGURE 20.



(Fig. 23), wiring looms complete with junction boxes, plug sockets and all the necessary ancillaries, and to place these components on supports, the positions of which have been carefully pre-determined, with the minimum of fixing required and consequently the least expenditure of labour.

A method which is believed to be original (it is apparently now being applied by Lockheed for the manufacture of the Electra) has also been used in France during the past few years. By this method a full scale model of the aircraft is made—a metal model using the same components, usually from rejected parts, as the structure itself. With this model, specialist and competent staff can take time to consider all the positions for the pipes, supports, wires and instruments. The positions and the shapes of the pipes are then determined by a process similar to the moulding process on the plaster models used for the structure (Fig. 24). In this way systems of piping, together with standard assemblies representing all the pipes, however complicated, can be worked out at leisure and made in due course by a sub-contractor, for example, and subsequently fitted on the aircraft without the least difficulty. These methods have been employed in France on aircraft such as the Vautour and the Mystere IVA, resulting in a very appreciable saving in time, particularly at the beginning of a series production.

Finally, the question of inspection and testing of all the equipment made is discussed. The method in use at the present time for the testing of series produced components before completion of the aircraft, consists of test benches which reproduce the hydraulic, electric or pneumatic power generated for actuating the various installations of the component under test, exactly as found in the aircraft. For instance, to test the wing installations, the power and the power outputs normally to be found in the fuselage are reproduced. When testing a fuselage and its air conditioning apparatus, we reproduce by means of compressors and heat exchangers a supply of compressed air at a temperature and in conditions corresponding to those actually existing, in practice, *e.g.* by bleeding air from the jet engines. All these installations are naturally expensive, cumbersome and complicated, but they have the signal advantage of providing for the final assembly line units which have already been tested and which fit well. All that is now needed is to tighten the pipe unions, make the electrical connections and make a brief overall check to verify that everything

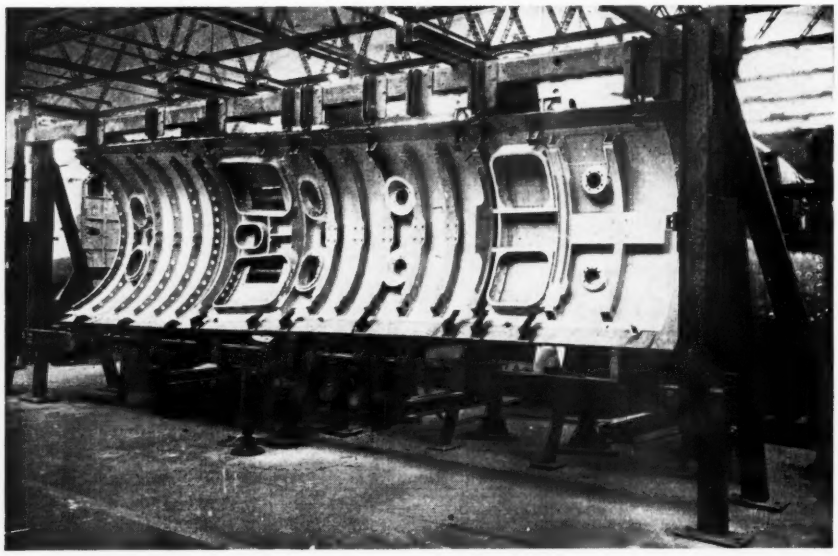


FIGURE 21.

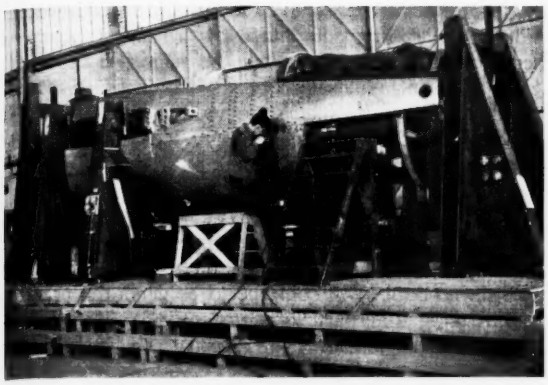


FIGURE 22.

is in working order. The aircraft, now completed, is ready for flight tests.

Normally the final stage in production is the fixed point of transition from manufacture to finished product, running the engines, and weighing. After various checks, including firing tests for military aircraft, radar checks and compass compensation, the aircraft is transferred to the acceptance group who perform a number of flight tests to ensure that the characteristics of the aircraft in flight are correct and that it can be delivered to the prospective user. Such flight test procedures are now familiar and it is superfluous and beyond the scope of this lecture to deal with them in detail.

In certain instances, the methods used in the motor car industry, for example, are relevant in the manufacture of aircraft. Of these, a very well known method is that of the single assembly line in which, for each operation of fitting and assembling, there is only one piece of equipment and one assembly jig. An increase in the rate of output is obtained merely by a greater differentiation of the line, that is reducing the number of operations performed on each assembly and each jig. This line is fed by parallel lines on which the sub-assemblies and their auxiliary equipment are being made. The parallel assembly lines may be situated, moreover, in a workshop separate from the main shop housing the final assembly line. This has proved a more economical method than one in which the rate of output is increased by using two sets of jigs for certain components. It costs much less to make single operation jigs on which

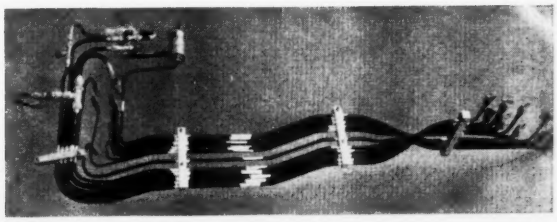


FIGURE 23.

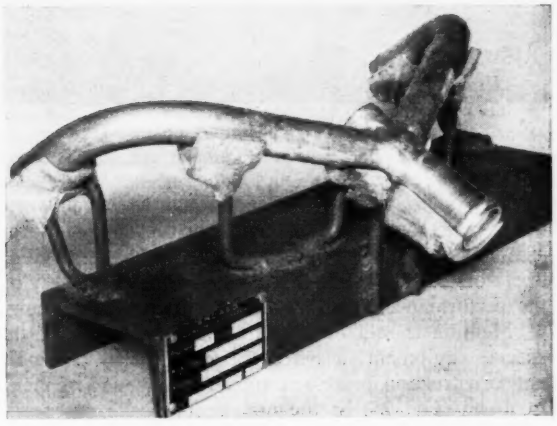


FIGURE 24.

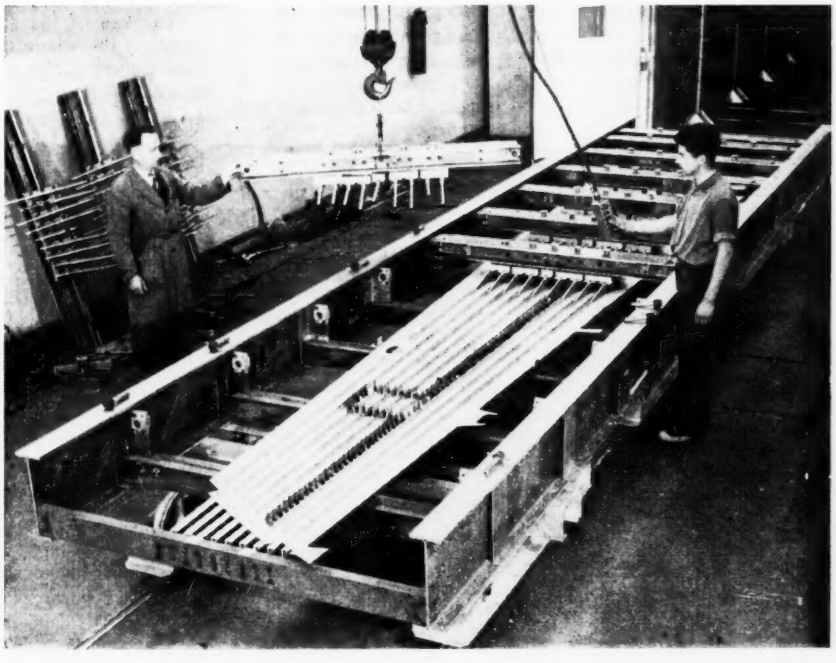


FIGURE 25. Metal-to-metal bonding.

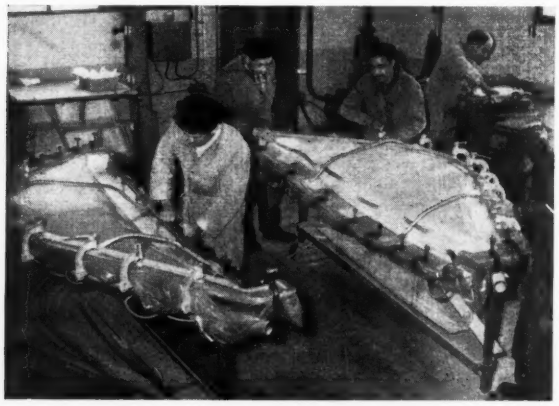


FIGURE 26.

to carry out an operation—even though we have a large number of such jigs—than to construct several large assembly jigs. A further advantage is that less skilled operators can be used, who can be instructed merely on the performance of a number of simplified operations.

Mention should be made, briefly in passing, of the special equipment designed for certain new assembly and construction processes, such as the gluing of metal to metal (Fig. 25) or the use of composite or special materials (various types of sandwich and honeycomb construction) (Fig. 26). The equipment itself is familiar and serves to ensure the good mating under pressure (Redux) or low pressure (Araldite) required during polymerisation of the glue, while maintaining close contact of parts which are frequently of complicated shape (honeycomb doors, for example). The only point which should be stressed is that factories applying these techniques should be equipped with large and efficient plant for the pickling and preparation of metal surfaces (Fig. 27), as well as well-ventilated and lighted workshops to avoid both the accumulation of dust and temperature variation.

FIGURE 27.

This brief paper will have demonstrated the considerable developments achieved in recent years on series production methods for the manufacture of aircraft. The introduction of plastic materials on the one hand and the ever increasing use on the other hand of very powerful industrial resources have enabled the aircraft industry to turn out large quantities of products which, as regards mechanical perfection, finish and interchangeability of all the parts yield nothing to the most finished products, for example, of the motor car industry. What developments does the future hold? Plastics no doubt will continue to be generally used for tool making and parts of constantly increasing complexity will be machined or forged to an even greater extent than at the present time. Aircraft will tend to become an aggregation of mechanical parts and assemblies, whereas only a short time since, as many may still remember, they were merely frail assemblies of wood, canvas and steel wirings.

What effect will missiles have on future developments? It is impossible to predict but it is probable that more new processes will appear. There is, for example, the manufacture of components from reinforced, pre-stressed concrete, which is being undertaken in France for certain missiles. In any case much remains to be done and to be learned. It may well be that research workers and engineers, aerodynamicists and calculators will not be idle in the years to come. No less certainly will production engineers also be fully occupied, with plenty to do, plenty to think about and plenty of material on which to exercise their inventive powers.

## APPENDIX I

### USE OF THE SINGLE LINE IN AIRCRAFT CONSTRUCTION

The use of the single line in aircraft construction is based on the whole cycle of operations performed during manufacture. This cycle may be defined as the longest period which elapses between the time of starting work on the raw materials used in an aircraft and the date of delivery of the finished aircraft.

It is obviously of prime importance, for the following reasons, to reduce the time taken to complete this cycle.

A reduction decreases the total number of aircraft on the line, with a consequent reduction of tied-up capital and of the work in progress.

As a result, the number of square metres of factory space occupied is also less and the capital investment not so great. The time required before production starts is reduced and

the first aircraft are consequently delivered more quickly to the prospective users who are always eagerly awaiting them.

This method makes it easier to keep to a fixed programme and there is less likelihood of incurring contractual penalties.

The modifications which always occur at the beginning of a production contract are incorporated more easily in the line, since this will possess less inertia, because of its shorter time to completion.

A closer examination of the factors likely to affect the reduction of the cycle reveals the following two categories: —

(*a*) Main parts
(*b*) Assembly operations, both of the structure and completed aircraft.

1. *Detail Parts*

The duration of the cycle in the case of a detail part is determined by the number of operations to be performed on one part, the number of operations that can be performed simultaneously, and the number of machines used. If the rate of turnover is high, the cycle can be reduced by the use of transfer machines capable of performing a number of successive operations in a very short time. This is the solution adopted at the present time in the motor car industry. For a medium rate of turnover the answer is to use either an increased number of machines or faster machines. With a low rate of turnover, a selective use of a few machines is possible but this obviously entails numerous setting-up and dismantling operations and long periods when a particular part is lying idle between various operations. It will at once be seen that low rates of turnover do not help to reduce the total cycle of operations—a fact well known to production engineers. It is therefore an advantage to reduce as far as possible the total number of operations on one and the same part, in particular, by using, whenever possible, pressings or castings in which the form of the rough part is very nearly that of the final form, thus reducing to a minimum the finishing machinery operations.

2. *Structure*

The cycle is proportional to the quotient of the total time divided by the number of possible fitters employed and also, the time during which sub-assemblies are lying idle between operations. It will therefore be seen that, both for the fitting together and the testing operations, it is important to pre-fabricate as much as possible away from the line, not to repeat various operations, *e.g.* testing, and finally to reduce the time taken for these operations.

Considerations such as these will provide a basis for the arrangement of the single line.

2.1. STRUCTURE OF THE LINE

This must be extended vertically and not horizontally, so as to have as large an area as possible in common with the single line.

Thus, one elementary operation requires only one jig and one team of fitters. An increase in the rate of turnover is then obtained simultaneously by an increasing sub-division of the component parts and a corresponding decrease in the working times required on sub-assemblies which are constantly increasing in number. These sub-assemblies which are produced on lateral lines are assembled into components or units which grow increasingly larger and more finished after each operation. They are then assembled on the central line, with working times reduced to the minimum. It is, for instance, of great advantage if all the supports for various ancillaries, such as pipes, accessories, electrical parts, and so on, can be placed in position in the sub-assembly stage and if the sub-assemblies of ancillaries such as the hydraulics, wiring and junction boxes, pipe assemblies, and so on, can be prepared separately in advance and made interchangeable, so that in the final assembly they need only be fixed on the supports prepared for them.

2.2. ADVANTAGES OF THE SINGLE LINE

The advantages accrue from the considerations governing the use of this method, and permit the employment of less skilled personnel, since each individual operator working in the line goes on repeating simple elementary operations. The reduction in the manufacturing time is improved, since this increases with a fall in the rate of turnover, and conversely, an increase in the rate is obtained simply by splitting up the elementary operations. Better interchangeability results at the different production stages and finally, the duration of the cycle is shorter, offering the advantages referred to in the first paragraph.

3. *Essential Conditions for the Single Line*

These conditions, which are not insuperable, are as follows: —

First of all, preparation must be much more extensive and each operation defined very exactly so as to make it possible for a relatively unskilled fitter to perform and repeat the operation without difficulty. Next, the organisation of the operations requires to be much more detailed with a view to equalising the duration of the work at each position and, consequently, reducing the idle times, although the rates of turnover are frequently modified and may vary appreciably during the starting-up period. This point is also to be borne in mind when the modifications which normally occur at this period are to be incorporated during manufacture, usually at the beginning. A current method for overcoming these difficulties is to provide in the lines a certain number of buffer positions on which the waiting components can either be allowed to remain temporarily, or undergo the additional operations required by the modifications introduced.

Finally, it is essential that the planning and design of an aircraft enable it to be broken down into sub-assemblies which can be assembled without fitting operations or without other complicated operations.

None of these objections is basically important and the single line can quite easily become a reality, as shown for example, by the series manufacture achieved according to this method in a relatively complex aircraft, such as the Vautour.

## APPENDIX II

A NEW METHOD OF ASSEMBLING AIRCRAFT STRUCTURES

The basic features of this method are: —

(1) The fixing of the basic skeleton components to the skin panels, as opposed to the conventional method of applying the skin panels to the basic skeleton.
(2) The extensive use of moulded plastic tooling.

1. *Assembly by Applying Basic Skeleton Components to Skin Panels*

In the conventional method, aircraft structures are usually assembled by first making a basic framework using

longerons and frames for the fuselage, and longerons, spars and ribs in the case of the wing and tail units, and then covering these skeletons with the skin panels. In the new method, on the other hand, each component part of the framework is separately applied to the skin panels and the final operation consists in the assembly of all the sub-assemblies thus produced.

The advantages of this method, as regards the quality of the aircraft manufactured, lie in the fact that it is easier to make the components of the basic structure exactly match the profile by placing them one at a time on the skin panels, than to apply the skin panels, particularly if they are rather thick, on a basic structure already assembled.

It is, indeed, no easy matter, even with complicated jigs, to cut out already assembled parts in such a way as to make them resemble theoretical profiles, if the skin is relatively thick and incapable of being adapted to the unevennesses in the basic skeleton, since in that case it is necessary either to place distance blocks where needed between the skeleton and the skin panels (which is not an industrial operation) or to readjust the skeleton to make it fit the skin, which means the employment of more highly skilled operators. On the other hand, if the skin is thin and adaptable to the unevennesses of the skeleton, the additional stresses set up by riveting, for example, produce a deterioration of the surface and, in certain aircraft, cause the skeleton outline to show beneath the skin.

The method has the further advantage of most frequently enabling the components of the basic skeleton to be fixed on each sheet metal panel and a number of sub-assemblies to be formed. This facilitates the application of the single line principle and ensures a decrease in manufacturing times and an increase in the number of operators working on the same aircraft and, consequently, reduces the manufacturing cycle (*see* Appendix I).

The saving in tooling is also considerable, since the positioning of the basic structural components is facilitated by the fact that the skin panel (particularly if it is thick) forms by itself a support for these parts.

## 2. *Moulded Plastic Tooling*

High speed aircraft of the kind generally produced in large aircraft factories must have skin panels of a standard of quality and accuracy difficult to achieve with older methods of tooling manufacture, even by using highly skilled workers and costly machines (*e.g.* copying milling machines).

A good method for producing this result is to replace the machining and fitting of gauges of steel tooling by low temperature moulding on a full scale model.

It will be realised that this technique can only be used if moulding materials without shrinkage, which do not require mechanical machining or entail complicated calculations for the scale reduction of the moulds, are available. In addition, the mechanical properties of these materials must be such as to make them withstand the stresses imposed on various forming and assembly tools. It should also be remembered that it is current practice to press alloys at a pressure of 300-400 kg./cm.$^2$ and that higher pressures will certainly be used in the very near future.

Phenol resins are now commercially available for solid moulding and ethoxyline resins for rolling and thin moulding. These resins have the following characteristics: Non-shrinking polymerisation, quick industrial application in ambient conditions, absence of need for highly specialised equipment, easy use by personnel after brief training.

Methods for the manufacture of such tooling are based on the repeated use of a master-model constructed from a working drawing and corrected here and there if necessary to produce a regular profile.

The model is an exact representation of the outside of the component to be made.

In the case of large dimensions (aircraft fuselage, for example) several models are used in succession, each model having one part in common with the preceding or following model to ensure accurate continuity of the profile. Various methods, all well known, have been used for making these models. It is not proposed to describe them here but merely to say that it is often of advantage to use for the lines of the basic skeleton thin sheet metal plates made directly from full scale drawings of the aircraft.

After completion of the profile (this usually entails a readjustment of the outline—an easy operation since the model is made of plaster, a high plasticity material) the reference lines, the position for the skeleton components in contact with the skin panels and the cross sections of the skin panels, are drawn with a scriber on the surfaces of the models.

Using the model which has been produced in this way the tooling is made entirely by moulding. The moulds are taken by contact with the models and give a clear reproduction of form and dimensions, at the same time bringing out in relief the depressed markings on the model. These moulds are basically of plaster mixed with cement to reduce shrinkage when used for making forming tools for detail parts. They are of laminated resin glass for the manufacture of assembly and testing tools.

## 2. *Tooling*

Tooling for detail parts is cast in the mould taken from models or in the negative impressions from these moulds. These moulds or negative impressions are reinforced simply by tubular steel structures made to approximate dimensions (an accuracy of half a centimetre is quite sufficient) the rigidity of which is effected by the large number of connecting links.

The tooling for forming the skin panels is cast directly in these moulds and can be made either of resin or of concrete (even in the case of tooling for large dimensions and simple form). This applies particularly for the drawing forms for large skin, fuselage or wing panels. The surface of this concrete tooling is often reinforced by applying a high resistance Daro cement, particularly at the corners which are very fragile.

The tooling for forming the structural parts in contact with the skin is cast in these moulds made from the plaster model constructed on the spot at the lower part of the component.

The assembly tools are generally moulded in ethoxyline resins, starting from laminated glass resin moulds taken by contact with the model. These moulds give rise in turn to plaster models of the structural parts. This method offers the following advantages:—

As the moulds all have a common origin, accuracy in the dimensions and form of the tools, as well as of the different interchangeability templates, is ensured easily.

Working with plastic materials does not require highly qualified operators. For example, it was possible to convert a carpentry and packing workshop, where the work had fallen off considerably, almost completely into a tooling workshop after a few weeks' instruction for the workers who had never before been concerned with the making of tooling.

The moulding process largely dispenses with the need

for costly machines such as the large milling machines, for machining the dies. Furthermore, as the work is performed in three dimensions and not from drawings to which the methods of descriptive geometry are applicable, practically no adjustment or perfecting of the tooling is necessary and the most complicated units can be assembled from the start, as proved by experience with several types of aircraft.

Finally, for skin panels and the corresponding structural parts a saving in the manufacturing time for the tooling is obtained which is all the more manifest the greater the complexity of the forms. For example, by conventional methods a fuselage spar of particularly complicated form could have been defined only by means of a large number of sections placed on a line with no possible geometrical definition. Numerous readjustments would almost certainly be necessary to the bending press tooling which could have been made only by milling and the whole operation would have lasted perhaps eight months. By the new method such a spar can be completed in a few weeks by constructing directly on the hollow model of the fuselage a plaster model of the spar itself and taking directly from this model the mould in which the resin press-tool enabling the final part to be made immediately and without touching up has been cast. This, from the first piece produced, is assembled on the part of skin which was itself formed by tooling derived from the model and without necessitating further adjustment in fitting.

## APPENDIX III

### Production Tests

The preceding appendices will have shown the importance of reducing the production time. One method of achieving this is to carry out tests during the production stage. These tests enable any faults in functioning and any manufacturing defects to be detected immediately, and remedied without the necessity of long and complicated dismantling and reassembling operations, or without having to begin again all the operations of testing which, directly or indirectly, may be conditioned by the placing in position of a new ancillary.

This method, on the other hand, requires a much larger number of test benches and working positions, since each elementary operation must be performed by means of a power system representing that in the corresponding part of the aircraft. Instead of having merely a general system for functioning tests on a group of ancillaries, *e.g.* all the hydraulics, devices for supplying hydraulic power must be provided for each of the ancillaries as and when they are installed. It may be observed in this connection that this essential condition is largely alleviated if the aircraft is so designed as to enable the component parts to be installed as complete units.

For example, apparatus for testing the fuel system in an aircraft where the fuel is stored both in the fuselage and in the wings, will include a number of devices on the fuselage assembly line for testing the filling, emptying and pressure-tightness of the tanks and the circuits. A similar device will be installed on the wing assembly line, which may be in a different workshop, and finally there will be testing equipment for the complete aircraft after the individual components have been assembled.

These three testing sets will obviously cost more than the single installation for testing the complete aircraft, but experience has shown that the initial outlay is very quickly covered by the time saved in being able to discover from the very beginning any possible defects in the fuel system and providing for their elimination in the components still to be assembled.

These principles are clearly applicable to the hydraulic, electrical and air conditioning installations.

An alternative method, which can, moreover, be applied simultaneously, is to construct test rigs which exactly reproduce the installations in the real aircraft as regards the number, shape and location of parts such as pipes, electric wiring, and so on. Large components, *e.g.* undercarriage or large armaments, are then mounted on these rigs for the purpose of functioning tests and there is no need to stop an aircraft on the production line because of a fault in functioning.

Such installations are also costly, but they quickly pay for themselves as soon as a high rate of production is achieved.

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Mr. Henry Gardner, *Fellow*, proposed the vote of thanks to the Lecturer:—

MR. HENRY GARDNER: I was delighted to accept the invitation to give this vote of thanks for two reasons. In the first place this is an opportunity that I have wanted for some time, to express what I am sure is felt by many aeronautical engineers, our appreciation of the recent rapid strides made in the French industry, particularly in this question of tooling for production. It is a very short time indeed since the French Aircraft Industry recommenced production, and I am glad to have this opportunity to say how much we are impressed with the strides they have made and their recovery in these past few years.

In the second place I would like to congratulate Colonel Badre on creating another "first." This is the first lecture on production that I can remember in any named series. It is certainly the first in the Louis Blériot Lectures. There has never been a lecture on Production Engineering in the Commonwealth Lectures and we have to go back in the Wilbur Wright series some 26 years since the subject was discussed, and then when Glenn Martin gave his lecture it was not the main subject of the paper.

There are so many difficulties in arranging production lectures that I am sure all those associated with the Branches or the organisation of the Lectures Committee will realise that it is extremely difficult to get a man to speak on Production Engineering. Our Production Engineers are not vocal people; in fact they are rather shy. I think one realises this when one remembers that, during the last war, this country was able to set up a Ministry of Aircraft Production far more effectively than, in times of peace, we can appoint a Professor of Aircraft Production.

There are so many comments that one would like to make on the paper that it would be invidious to attempt to make them all. But there are a few which I feel I should mention. I would like to mention the question of forgings. This paper has brought out how we are now dealing with large masses of material and how important the whole problem has become; also I agree very much with what was said about copy milling and other milling machines. I believe one might mention that the new high speed routers also offer some scope in this direction and with a very reduced price. I was also interested to hear the comment on chemical milling as we call it, or chemical etching. There is no doubt that this has a future and I believe that preliminary tests show that it has fewer disadvantages than was originally believed. Certainly some recent fatigue tests indicate that and I was pleased indeed to see chemical milling brought out in the paper. There is certainly a future for this process and a great deal of development is required.

I was also pleased to read the compliment paid to the Fairey Aviation Company for envelope jigging. There is no doubt that this logical approach towards securing an accurate profile has come to stay and is being adopted more widely.

The use for plastic models was mentioned and I was impressed with the way in which quite crude and elementary jigs are produced by the aid of plastics. This has been under development for some time and it is pleasing to see that the French are introducing these methods so cheaply.

The reference to the use of metal balls to simulate hydraulic pressure reaction was interesting and was probably novel to many although it is obviously a valuable asset in production development.

Reference was made in passing to the large 50,000 ton presses and these were accepted by a lecturer as things that have come to stay. I wonder if in fact this is true. The large forging press, as so many will remember as a subject for some acrimonious discussion in certain committees, is probably not so near in terms of the future as we thought some years ago and I would express some doubts in fact on how far the really large hydraulic press has come into production engineering in view of our use of steel for these high speed aircraft.

Mention was made of automation and here I believe we shall go farther than our lecturer indicated. I believe it is going even farther on comparatively small assembly lines where numbers of from 25 upwards are concerned. The milling machines are here already. Drilling machines are coming and the use of punched cards and the tape is obviously not far away. I believe that this lecture has revealed a start in this direction which will go much farther than we have expected in the past.

Our lecturer also drew our attention to a very significant change. He pointed out that only a short time ago, as many may still remember, these aircraft were frail assemblies, made of wood, canvas and wire. Our lecture tonight has certainly shown how far we have come since the early days of the last war when a considerable proportion of the aircraft were fabric covered and the lecture has brought that out clearly in addition to showing how far the French industry has progressed.

I would therefore like to express my pleasure in proposing this vote of thanks. We know from experience how very difficult it is to get someone to speak on this subject and I know too that it is a very brave man who gets up and speaks on production engineering to production engineers. We have from Colonel Badre's past his record of courage. I am therefore very pleased indeed to propose this vote of thanks.

MR. M. B. MORGAN: It is with considerable pleasure that, reinforcing what Mr. Henry Gardner has just said, I express on behalf of us all our thanks for the most stimulating lecture we have just heard from Colonel Badre. During the coming years increasingly strong ties will undoubtedly be forged between ourselves and our neighbours across the Channel. Aeronautics knows no frontiers and occasions such as the Louis Blériot Lecture afford an opportunity of emphasising how much we gain by the interplay of ideas and arguments between scientists and technicians of different nationalities engaged in this most fascinating of all arts—the art of flying.

On the research side, with which I am most familiar, we have the happiest of relationships with Monsieur Roy and his O.N.E.R.A. team, with the French Air Ministry and with the Service and Design interests in France. We look at one another's wind tunnels. We exchange wind tunnel models and we keep abreast of our mutual thinking. One of the things we enjoy very much indeed is the verve and liveliness of the present French aeronautical scene. In particular the boldness with which new ideas are tried in flight in order to advance knowledge. We are also in debt to the ingenuity of the French flight instrumentation people who have certainly not lagged in meeting the need for small, compact and reliable apparatus tailored to flight test needs.

Now bright research ideas are no good at all without a strong follow-up in the design organisations and production units. Colonel Badre has shown us the calibre of French thought on production techniques and it is with the greatest pleasure that I second this vote of thanks.

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Following the Lecture a dinner was given by the President and Council of the Society at 4 Hamilton Place, at which the following were present:—

Monsieur L. S. Armandias, Representative in Great Britain of the Association Française des Ingénieurs et Techniciens de l'Aéronautique.

Monsieur Paul Badre, Louis Blériot Lecturer, 1957. Dr. A. M. Ballantyne, T.D., B.Sc.(Eng.), Hon.F.C.A.I., A.F.I.A.S., F.R.Ae.S., Secretary, Royal Aeronautical Society. Air Commodore F. R. Banks, C.B., O.B.E., M.I.Mech.E., F.R.Ae.S., Louis Blériot Lecturer, 1948; Director, Bristol Aeroplane Co. Ltd.; Member of Council of the Royal Aeronautical Society. Captain K. J. G. Bartlett, C.B.E., M.Inst.T., M.S.A.E., A.F.R.Ae.S., President of the Federation Aéronautique Internationale. Professor A. D. Baxter, M.Eng., M.I.Mech.E., F.R.Ae.S., Deputy Principal, College of Aeronautics, Cranfield; Member of Council of the Royal Aeronautical Society. The Lord Brabazon of Tara, G.B.E., M.C., Hon.F.R.Ae.S., President, Royal Aero Club; Past President, Royal Aeronautical Society. Major G. P. Bulman, C.B.E., B.Sc., F.R.Ae.S., Honorary Treasurer, Royal Aeronautical Society; Director of Construction of Research Facilities, Ministry of Supply. Mr. A. F. Burke, O.B.E., M.Inst.T., F.R.S.A., Director, de Havilland Holdings Ltd.

Sir Sydney Camm, C.B.E., F.R.Ae.S., Past President, Royal Aeronautical Society; Director and Chief Designer, Hawker Aircraft Ltd. Mr. J. R. Christie, Private Secretary to the Minister of Supply. Dr. R. Cockburn, C.B., O.B.E., Director of Guided Weapons and Electronics, Ministry of Supply.

Monsieur l'Ingénieur General Daum, Assistant Director at the Direction Technique et Industrielle, Ministère de l'Air. Mr. Handel Davies, M.Sc., A.F.I.A.S., F.R.Ae.S., Deputy Director General, Future Systems, Ministry of Supply; Member of Council of the Royal Aeronautical Society. Mr. L. J. Dunnett, C.M.G., Deputy Secretary (Air), Ministry of Supply. Major-General C. A. L. Dunphie, C.B., C.B.E., D.S.O., Chairman, Vickers-Armstrongs (Aircraft) Ltd.

Mr. L. G. Frise, B.Sc., A.F.I.A.S., F.R.Ae.S., Director of Special Projects, Blackburn and General Aircraft Ltd.; Member of Council of the Royal Aeronautical Society.

Mr. H. H. Gardner, B.Sc., F.R.Ae.S., Chief Engineer (Military), Vickers-Armstrongs Ltd.; Member of Council of the Royal Aeronautical Society. Sir Arthur Gouge, B.Sc., F.I.A.S., M.I.Mech.E., Hon.F.R.Ae.S., Vice-Chairman and Chief Executive, Saunders-Roe Ltd.; Past-President, Royal Aeronautical Society.

Mr. Raoul Hafner, F.R.Ae.S., Chief Designer (Helicopters), Bristol Aeroplane Co. Ltd.; Louis Blériot Lecturer, 1954. Sir Arnold A. Hall, M.A., F.R.S., F.R.Ae.S., Vice-President, Royal Aeronautical Society; Technical Director, Hawker Siddeley Group. Mr. P. A. Hearne, D.C.Ae., D.I.C., Grad.R.Ae.S., Helicopter Project Engineer, Project and Development Branch, British European Airways; Member of Council of the Royal Aeronautical Society. Mr. A. Hillier, O.B.E., J.P., F.C.I.S., A.F.R.Ae.S., Chairman and Managing Director, Sperry Gyroscope Co. Ltd.

Monsieur J. Jarry, President of l'Association Française des Ingénieurs et Techniciens de l'Aéronautique. Monsieur de Jenlis, Ingénieur en Chef de l'Air. The Rt. Hon. Aubrey Jones, M.P., Minister of Supply. Mr. E. T. Jones, C.B., O.B.E., M.Eng., F.R.Ae.S., President of the Royal Aeronautical Society; Director General of Technical Development (Air), Ministry of Supply. Air Marshal Sir Owen Jones, K.B.E., C.B., A.F.C., B.A., D.I.C., M.I.Mech.E., F.R.Ae.S., Aeronautical Consultant; Member of Council of the Royal Aeronautical Society.

Mr. H. Knowler, A.M.I.C.E., F.R.Ae.S., Aeronautical Consultant; Louis Blériot Lecturer, 1952.

Mr. B. P. Laight, M.Sc., A.M.I.Mech.E., F.R.Ae.S., Chief Designer (Aircraft), Blackburn and General Aircraft Ltd.; Member of Council of the Royal Aeronautical Society. Mr. R. L. Lickley, B.Sc., D.I.C., M.I.Mech.E., F.R.Ae.S., Technical Director and Chief Engineer, Fairey Aviation Co. Ltd.

Mr. W. R. McGaw, C.B., F.R.Ae.S., Director General of Aircraft Production, Ministry of Supply. General G. du Merle, F.R.Ae.S., Head of Aviation Department, Société des Petroles Shell-Berre; Louis Blériot Lecturer, 1953. Mr. M. B. Morgan, M.A., F.R.Ae.S., Deputy Director, Royal Aircraft Establishment; Member of Council of the Royal Aeronautical Society. Sir Cyril Musgrave, K.C.B., Permanent Secretary, Ministry of Supply.

Mr. H. G. Nelson, M.I.C.E., M.I.Mech.E., M.I.E.E., Managing Director, English Electric Co. Ltd.

Air Chief Marshal Sir Claude Pelly, K.C.B., C.B.E., M.C., Controller of Aircraft, Ministry of Supply. General de Brigade Aerienne A. Puget, D.S.O., Air Attaché to the French Embassy.

Mr. N. E. Rowe, C.B.E., B.Sc., F.C.G.I., F.I.A.S., F.R.Ae.S., Past President, Royal Aeronautical Society; Technical Director, Blackburn and General Aircraft Ltd. Sir Harold Roxbee Cox, Ph.D., D.I.C., B.Sc., M.I.Mech.E., F.I.A.S., F.R.Ae.S., Past President, Royal Aeronautical Society; Consulting Engineer.

Mr. B. S. Shenstone, M.A.Sc., F.C.A.I., A.F.I.A.S., F.R.Ae.S., Chief Engineer, British European Airways; Member of Council of the Royal Aeronautical Society.

Mr. Eric Turner, Managing Director, Blackburn and General Aircraft Ltd.

Dr. P. B. Walker, C.B.E., M.A., F.R.Ae.S., Head of Structures Department, Royal Aircraft Establishment; Member of Council of the Royal Aeronautical Society. Mr. L. A. Wingfield, M.C., D.F.C., A.R.Ae.S., Solicitor to the Royal Aeronautical Society. Mr. W. F. S. Woodford, Secretary, Institution of Production Engineers.

# Turbo-Prop Performance Analysis and Flight Planning

## *A Viscount Operator's Approach*

by

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### 1. Introduction

When Viscount 720 aircraft were delivered to Trans-Australia Airlines it became clear that increased attention would have to be given to performance analysis and the preparation of flight planning data.

Previous operational experience had been restricted to piston-engined aircraft which, for flight planning purposes, could be regarded as cruising at a certain air speed and burning fuel at a certain rate. Temperature effects were negligible because it was the accepted practice to restore power on hot days by slightly increasing boost settings. Altitude effects, although not truly negligible, were certainly small and could be covered by using flight planning figures from the conservative side of the range. With the Viscount, however, the specific range at cruising altitude was found to be almost twice its sea level value and a 10°C. rise in temperature was capable of reducing true air speed by 20 knots.

Some European operators had issued their crews with pages of tables showing speeds, consumptions, climb times and climb fuels for all combinations of weight, altitude and air temperature. From these they had to extract the appropriate figures and build up a detailed flight plan, making the necessary corrections for wind on each phase of the flight. For Australian operations, with a planned utilisation of around 9 hours per day and short turnarounds allowing the captain only 10 to 15 minutes for flight planning, a more direct method had to be devised. Graphical presentation was chosen, although not without some resistance from the older and more conservative pilots, and for each stage a chart was drawn up to show the total flight time and flight fuel in terms of altitude, temperature and mean wind component. Fig. 1 illustrates such a chart for the Melbourne-Adelaide stage.

The first Viscounts delivered to Trans-Australia Airlines (T.A.A.) were fitted with Dart 505 engines and a series of charts was rapidly produced from Vickers performance data. In practice, these charts were found to be conservative at the higher altitudes; in fact, the aircraft could be operated quite satisfactorily at altitudes higher than the ceiling specified in the Vickers data. For the initial operations on the east coast routes this did not matter greatly and the charts continued in use for over a year.

The later aircraft were fitted with Dart 506 engines and slipper tanks and were destined to be used on the 1,200 nautical mile stage from Adelaide to Perth against headwinds frequently greater than 50 knots. This was obviously a critical stage and, as it had to be operated in competition with DC-6 aircraft, intermediate landings for refuelling could only be tolerated on rare occasions. High altitudes were clearly essential and the performance of the aircraft at those altitudes had to be known and understood. A series of checks on Vickers 506 performance data revealed a type of conservatism similar to that found in the 505 data; it was therefore necessary to re-establish the climb, cruise and descent performance of the aircraft.

The techniques used had to be tailored to suit a small organisation which could only spare two engineers to do the flight observation, reduction, analysis and calculation of planning charts. They are therefore somewhat different from the techniques used by the larger organisations and the object of this paper is to explain them in the hope that they may be of use to other small organisations faced with the need to do similar work. Some information on the derivation and use of the planning charts and on methods of operating for best economy of maximum range is also included.

The techniques described are only applicable in detail to engines of the single-spool type, such as the Dart. However, twin-spool engines are affected by the same number of independent variables so it should be possible to measure their performance by somewhat similar methods with appropriate variations in detail. For example, tests would probably have to be made at optimum power turbine r.p.m. rather than at optimum jet pipe temperature.

NOTATION

$A$ a constant, $= C_{D_0} \frac{1}{2} \rho_0 S$

$B$ a constant, $= \dfrac{2kW_s^2}{\pi \rho_0 b^2}$

$b$ wing span, ft. (93·7 for V720)

$C$ virtually a constant, $= 550 m\eta\tau \dfrac{N_s}{N_{max}}\left(1+\dfrac{\Delta P}{\eta P}\right)$

$C_{D_0}$ profile drag coefficient

$C_P$ propeller power coefficient, $= \dfrac{550P}{\rho n^3 d^5}$

*Received August* 1956

$D$ total aircraft drag, lb.
$d$ propeller diameter, ft.
$F$ total fuel flow (4 engines) lb./hr.
$f$ function of . . . .
$J$ propeller advance coefficient, $= \dfrac{V}{nd}$
$K$ climbing speed factor, $= \dfrac{V_i \text{knots}}{\sqrt{W}}$
$k$ induced drag factor
$m$ number of engines
$N$ engine revolutions per minute
$N_s$ standard reference r.p.m. (13,600 for Dart)
$N_{max}$ take-off r.p.m. (14,500 for Dart)
$n$ propeller revolutions per second
$P$ shaft horse power per engine
$P_{RR}$ s.h.p. from Rolls-Royce brochure
$P_{iw}$ power function, $= \dfrac{P\sqrt{\sigma}}{W_R^{3/2}}$
$\Delta P$ horse power due to jet thrust per engine
$p$ ambient air pressure, lb./ft.$^2$
$r$ $\dfrac{\text{propeller}}{\text{engine}}$ gear ratio (0·106 for V720)
$S$ wing area, ft.$^2$
$T$ ambient air temperature, °K (or °C if stated)
$T_3$ turbine inlet temperature, °K
$T_4$ jet pipe temperature, °K
$T_{40}$ optimum jet pipe temperature, °K
$V$ true air speed, ft./sec. (or knots if stated)
$V_i$ equivalent air speed, ft./sec. (or knots if stated)
$V_{iw}$ speed function, $= \dfrac{V\sqrt{\sigma}}{W_R^{1/2}}$
$v_c$ rate of climb, ft./sec. (or ft./min. if stated)
$v_{ciw}$ rate of climb function, $= \dfrac{v_c\sqrt{\sigma}}{W_R^{1/2}}$
$W$ weight of aircraft, lb.
$W_s$ standard reference weight (56,000 for V720)
$W_R$ relative weight, $= \dfrac{W}{W_s}$
$\eta$ propeller efficiency
$\theta$ relative air temperature, $= \dfrac{T}{288}$
$\tilde{\omega}$ relative air pressure, $= \dfrac{p}{2116}$
$\rho$ air density, slugs/ft.$^3$
$\sigma$ relative air density, $= \dfrac{\rho}{0{\cdot}00238}$

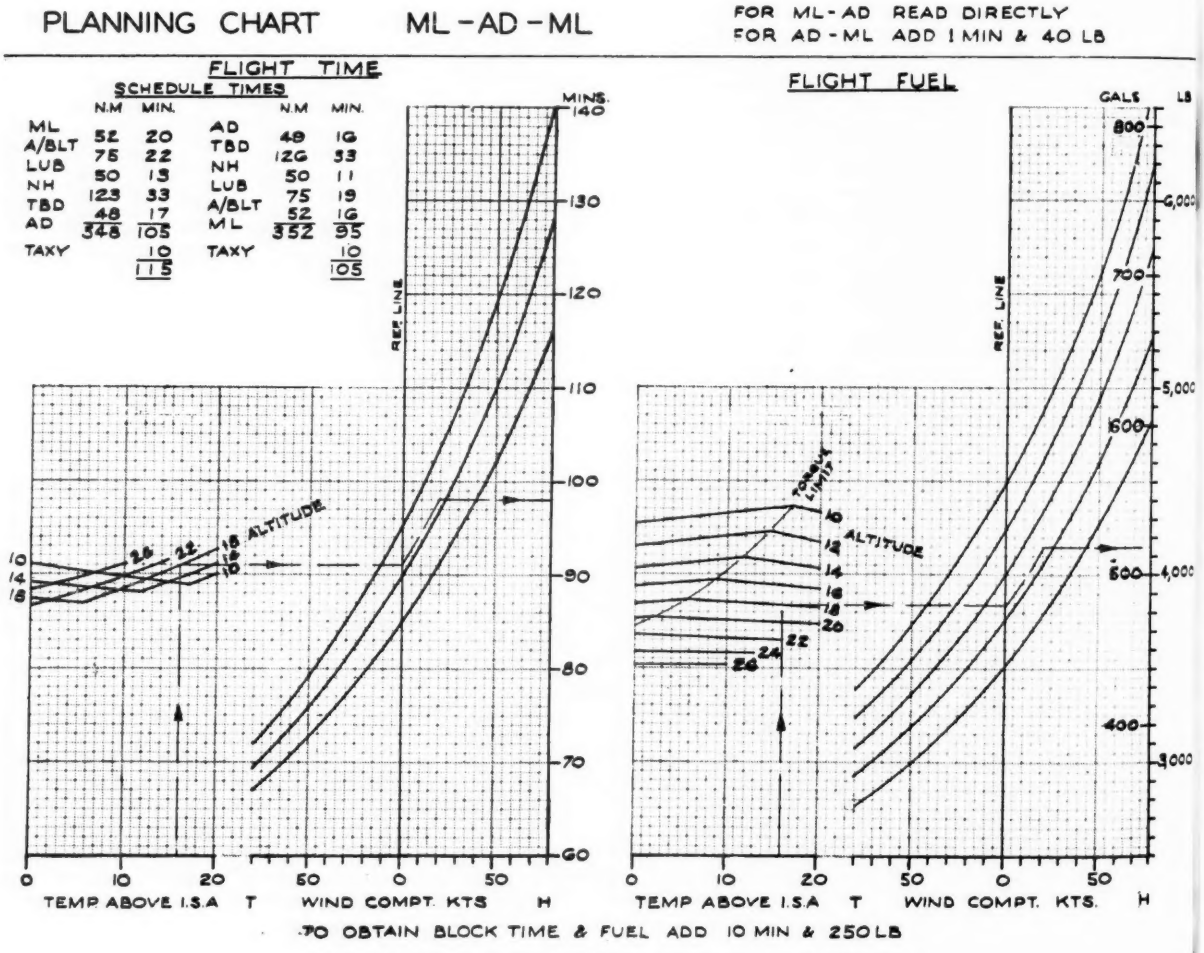



FIGURE 1. Typical route planning chart. Melbourne-Adelaide stage.

$\tau$ torquemeter constant, $= \dfrac{PN_{max}}{\psi N}$

$\psi$ indicated torque pressure per engine, lb./in.$^2$

$\psi_{tw}$ torque function, $= \dfrac{\psi\sqrt{\sigma}}{W_R{}^{3/2}}$

## 2. Comparison of the Turbo-Prop Engine with Other Power-Plant Types

The normal method of operating a *piston-engined* commercial aircraft is to set boost and r.p.m. to give a known power output. A table of recommended boost and r.p.m. settings at various altitudes is provided for the pilot and he applies these with a small boost adjustment to restore power when temperature is above standard. Power is therefore a controlled variable and, for practical purposes, the level speed of the aircraft can be expressed in terms of three quantities only: —

$$V = f(P, \sigma, W) \quad . \quad . \quad . \quad (1)$$

Closer examination of the equations for the airframe and propeller: —

$$550\, m\eta P = C_{D_0} \tfrac{1}{2} \rho S V^3 + \frac{2kW^2}{\pi \rho V b^2} \quad . \quad (2)$$

and

$$\eta = f(C_P, J) = f(P, \sigma, N, V) \quad . \quad (3)$$

shows that r.p.m. has an indirect effect by varying the efficiency of the propeller. However, the range of r.p.m. used for cruise is normally narrow and, with a constant speed propeller, the practical effect of r.p.m. on level speed at constant power is generally small.

In a *turbo-jet* aircraft the fuel flow is adjusted by means of the throttle lever to give a chosen r.p.m., with a provision that this r.p.m. must be reduced if the jet pipe temperature exceeds a certain limiting value. Power is an uncontrolled variable determined by r.p.m., air temperature and pressure and, since it cannot be expressed directly in terms of density, the level speed of the aircraft is determined by four independent quantities: —

$$V = f(N, \tilde{\omega}, \theta, W) \quad . \quad . \quad . \quad (4)$$

In a *turbo-prop* aircraft with a single-spool engine of the Dart type the problem is complicated by the provision of facilities for varying r.p.m. and power independently. The throttle lever is connected directly to the propeller constant speed unit (P.C.U.) and by way of a fuel trimming control to the fuel control unit (F.C.U.). This is illustrated diagrammatically in Fig. 2.

When the throttle is opened the r.p.m. and fuel flow are increased together in such a way as to produce the desired jet pipe temperature (J.P.T.) in standard air temperature conditions. As the aircraft ascends with the throttle position fixed, a capsule in the F.C.U. adjusts the fuel flow to maintain the desired J.P.T., provided again that the air temperature is standard. However, if the air temperature rises above standard, the J.P.T. also rises above its desired value; it is then necessary to "trim back" the fuel flow until the desired J.P.T. is regained. This process of trimming back varies the power of the engine and the performance of the aircraft without any change in $N$, $\tilde{\omega}$, $\theta$ or $W$, so a fifth independent variable is introduced. The most obvious indication of the extent to which the fuel flow has been trimmed is the J.P.T.; thus the level speed of the aircraft is usually expressed in the form: —

$$V = f(N, \tilde{\omega}, \theta, W, T_4) \quad . \quad . \quad (5)$$

When turbo-prop performance work is first encountered, there is a tendency to regard J.P.T. as a variable of secondary importance such as cylinder head temperature (C.H.T.) in a piston engine. If the J.P.T. is within about 20° of its usual value, that is often accepted as good enough. In point of fact, it is far from good enough; whereas a low C.H.T. normally only means that gills have been opened farther than usual and has little effect on engine power, a low J.P.T. means that the fuel flow to the engine is below normal. With the Viscount, a 20°C. drop in J.P.T. reduces engine power by about 6 per cent and, when cruising at 20,000 ft., this reduces true air speed by about 8 knots. It is therefore most important, when carrying out performance measurements on turbo-prop aircraft, to take care in the setting of J.P.T. Unfortunately, the J.P.T. gauges in the Viscount are not well suited to this; 20°C. is represented by only about 1/16 inch of needle movement.

The progressive increase in the number of variables from the piston-engine equation (1) to the turbo-jet equation (4) and then to the turbo-prop equation (5) is often the cause of some alarm. It should be realised, however, that equation (1) is derived solely from airframe and propeller formulae. Therefore, if the shaft horse power of a turbo-prop engine can be measured by a torquemeter and the residual jet power is comparatively small and roughly proportional to shaft horse power, there is no reason why equation (1) should not be applied. Equation (5) certainly has the advantage that r.p.m. rather than power is the controlled variable in a turbine engine but, if power can be satisfactorily measured, it can still be used as a variable in test and analysis work.

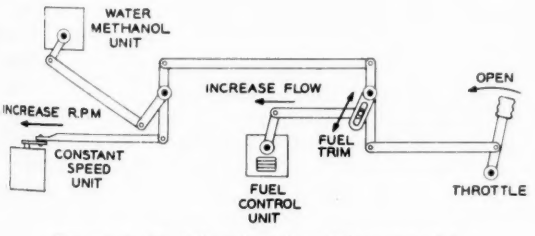



FIGURE 2. Dart throttle linkage (diagrammatic).

## 3. Two Methods of Analysing Cruise Performance

The first approach to the analysis of cruise performance was an attempt to apply the standard non-dimensional method set out in The Royal Aeronautical Society's Performance Data Sheets RT1/0 and RT1/1. Because of the wide differences observed between the torques of the various engines in flight, the torquemeters were regarded with great suspicion and this method had

the apparent advantage of circumventing them. Furthermore, the author had considerable experience in the application of non-dimensional methods to turbo-jet aircraft and a high regard for them.

Some time later a series of torquemeter readings were plotted as part of an investigation into the effect of the engine torque limit on the cruising speed of the aircraft. A plot of torque against speed with both variables corrected for weight and air density in a manner suggested by the American $P_{iw}V_{iw}$* method produced a good experimental line. The earlier distrust of torquemeter readings was thus shown to be unjustified. It is now accepted that a series of similar turbo-prop engines trimmed to a specified J.P.T. have a much greater spread of power than a series of similar piston engines; therefore torque variation between engines does not necessarily indicate torquemeter inaccuracy. An alternative method of analysing cruise performance based on the use of engine torque has now been developed and found to be more direct and broader in its application than the standard non-dimensional method. Although some approximations are involved, the results are sufficiently accurate for airline purposes.

The two methods are discussed in detail below.

### 3.1. STANDARD NON-DIMENSIONAL METHOD

From equation (8) of R.Ae.S. Performance Data Sheet RT1/0: —

$$V/\sqrt{\theta} = f(N/\sqrt{\theta}, W/\tilde{\omega}, T_4/\theta).$$

In the Dart 506 engine J.P.T. is adjusted by fuel trimming to

$$540°\text{C.} + \frac{\text{Indicated Outside Air Temperature (°C.)}}{2}$$

at all r.p.m. in the climb and cruise range. This is an empirical rule which is supposed to produce the desired turbine inlet temperatures laid down in the Rolls-Royce brochure of engine performance data (TSD533).

Since $V/\sqrt{\theta}$ is effectively Mach number,

$$\text{I.O.A.T.} = f(\theta, V/\sqrt{\theta}).$$

Thus optimum J.P.T., $T_{4o} = f(\theta, V/\sqrt{\theta})$

and, if J.P.T. is always adjusted to its optimum value: —

$$V/\sqrt{\theta} = f(N/\sqrt{\theta}, W/\tilde{\omega}, \theta).$$

At a *fixed* cruise *r.p.m.* and *optimum J.P.T.*: —

$$V\sqrt{\theta} = f(W/\tilde{\omega}, \theta) \quad . \quad . \quad (6)$$

Under the same conditions the fuel flow is given by: —

$$F/(\tilde{\omega}\sqrt{\theta}) = f(V/\sqrt{\theta}, \theta) \quad . \quad . \quad (7)$$

Combining (6) and (7): —

$$V/\sqrt{\theta} = f(W/\tilde{\omega}, F/(\tilde{\omega}\sqrt{\theta})) \quad . \quad . \quad (8)$$

Level flight tests were made at 13,600 r.p.m., the normal cruise setting, with chosen values of $W/\tilde{\omega}$ ranging in steps of 10,000 from 100,000 to 140,000. As most of the tests were made on revenue-earning flights, the weight of the aircraft was determined by factors outside the control of the technical staff and the altitude had to be varied to obtain the desired $W/\tilde{\omega}$. Fortunately the Viscounts were operating at higher altitudes than the bulk of the air route traffic and the permission of Air Traffic Control for a temporary change in altitude could usually be obtained. The fuel flows were measured by timing the fuel gone over a six minute period while the air speed was stabilising.

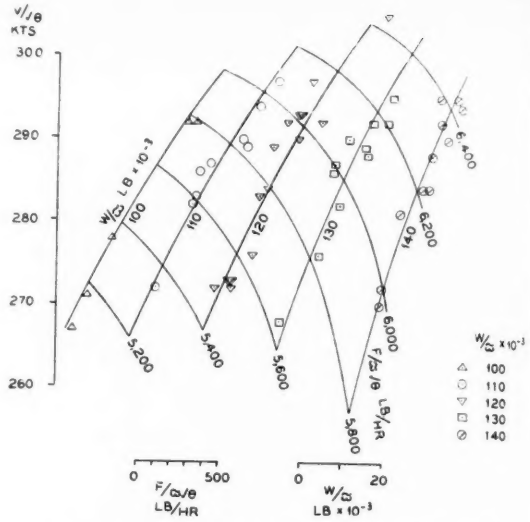



FIGURE 3. $V/\sqrt{\theta}$, $W/\tilde{\omega}$, $F/(\tilde{\omega}\sqrt{\theta})$ carpet, 13,600 r.p.m.

Figure 3 is a carpet of $V/\sqrt{\theta}$ in terms of $W/\tilde{\omega}$ and $F/(\tilde{\omega}\sqrt{\theta})$ derived from the test points. This carpet, which was based on equation (8), was found to have less scatter than one based on equation (6). Presumably any slight inaccuracies in the setting of r.p.m. were partly corrected out when speed was plotted against fuel flow rather than temperature. The maximum scatter of points from the lines forming the carpet is 5 knots T.A.S. or 2 per cent.

Figure 4 is a graph of $F/(\tilde{\omega}\sqrt{\theta})$ against temperature. This parameter is also affected by $V/\sqrt{\theta}$ but the variation with $V/\sqrt{\theta}$ could not be distinguished from the scatter of the test points so a single mean line was drawn. The maximum scatter of points from the mean line is 3 per cent and all points are above the line deduced from the Rolls-Royce brochure.

It is understood that, after tests made in the United Kingdom, this non-dimensional method was discarded as being practically unworkable. The tests just described show that it can be made to work if sufficient care is taken in the setting of J.P.T., although the alternative method described below is considered preferable. Possibly some of the difficulties encountered in the United Kingdom were due to the fact that in sub International Standard Atmosphere (I.S.A.) conditions, full fuel trim is not sufficient to bring the J.P.T. up to its optimum. If tests were made below I.S.A. this would introduce another variable. For Australian purposes performance data below I.S.A. – 5 is not required and small corrections can be made for the loss in performance due to the J.P.T. drop in I.S.A. – 5.

*Airplane Testing and Performance. Albert C. Reed. *Journal of the Aeronautical Sciences*, February 1941. This method now appears to be in general use in the U.S.A. by The Douglas, Convair, Lockheed and Boeing Companies.

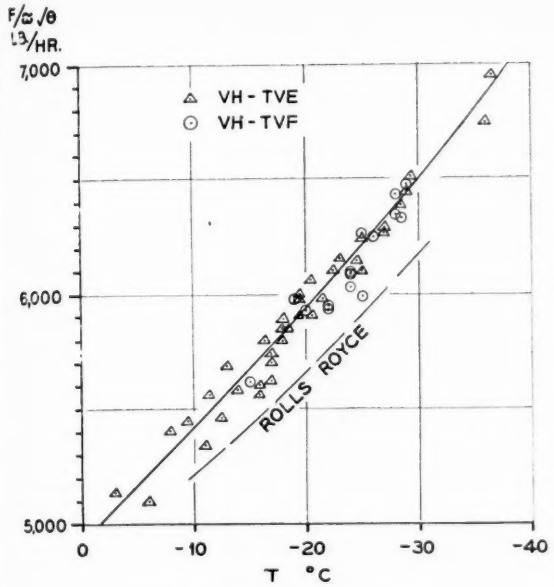



FIGURE 4. Fuel flow, 13,600 r.p.m.

### 3.2. ALTERNATIVE METHODS USING TORQUEMETER READINGS

The American $P_{tw}V_{tw}$ method (*see* footnote on p. 394), as applied to piston-engined aircraft, is based on recasting the airframe equation (2) in the form: —

$$550\,m\eta P_{tw}=C_{D_0}\tfrac{1}{2}\rho_0 S V_{tw}^3+\frac{2kW_s^2}{\pi\rho_0 b^2}\frac{1}{V_{tw}}$$

where $$P_{tw}=\frac{P\sqrt{\sigma}}{W_R^{3/2}}$$

and $$V_{tw}=\frac{V\sqrt{\sigma}}{W_R^{1/2}}$$

For a turbo-prop aircraft with a small residual jet power $\Delta P$, this becomes: —

$$550\,m\eta P_{tw}\left(1+\frac{\Delta P}{\eta P}\right)=AV_{tw}^3+\frac{B}{V_{tw}}$$

where $A$ and $B$ are constants depending only on the geometry of the aircraft and the choice of $W_s$.

If a torquemeter constant $\tau$ is defined by

$$P=\tau\psi\frac{N}{N_{\max}}$$

the equation may be written: —

$$550\,m\eta\tau\psi_{tw}\frac{N}{N_{\max}}\left(1+\frac{\Delta P}{\eta P}\right)=AV_{tw}^3+\frac{B}{V_{tw}}$$

where $$\psi_{tw}=\frac{\psi\sqrt{\sigma}}{W_R^{3/2}}. \qquad . \qquad (9)$$

With a properly designed constant speed propeller the variation in propeller efficiency over the cruise range is very small. Furthermore, in an engine such as the Dart, the residual jet power is only about 5 per cent of the shaft horse power and under cruise conditions it varies roughly in proportion to the shaft horse power. Thus, with a small degree of approximation, the equation may be simplified to: —

$$C\frac{N}{N_s}\psi_{tw}=AV_{tw}^3+\frac{B}{V_{tw}}$$

where $A$, $B$ and $C$ are constants

or $$V_{tw}=f\left(\frac{N}{N_s}\psi_{tw}\right) \qquad . \qquad . \qquad (10)$$

The following table illustrates how small the error introduced by this approximation is likely to be: —

V720-506ST 13,600 R.P.M. CRUISE

| Altitude, ft. I.S.A.+ | 15,000 | | 25,000 | |
|---|---|---|---|---|
| | 0 | 15 | 0 | 15 |
| *Weight* 50,000 *lb.* | | | | |
| T.A.S. knots | 260 | 261 | 281 | 258 |
| $\eta$ per cent | 85·5 | 85·5 | 85·0 | 85·2 |
| $\Delta P/(\eta P)$ per cent | 5·2 | 4·7 | 5·8 | 6·1 |
| *Weight* 59,000 *lb.* | | | | |
| T.A.S. knots | 253 | 253 | 265 | 227 |
| $\eta$ per cent | 85·5 | 85·5 | 84·8 | 84·2 |
| $\Delta P/(\eta P)$ per cent | 5·4 | 5·0 | 6·3 | 6·4 |

Figure 5 is a graph of $(N/N_s)\psi_{tw}$ against $V_{tw}$ obtained from the level speed tests previously described. Two 12,000 r.p.m. points have also been added to enable the lower end of the curve to be extended. The maximum scatter from the mean line is only 2 per cent of speed and it is clear that, although a large number of points have been plotted, a line such as this could be determined from a much smaller number of tests.

The torque-speed graph is, however, only one-half of the story; it represents the behaviour of the airframe. A graph showing the torque produced by the engine is also required.

Returning to R.Ae.S. Data Sheet RT1/0: —

$$P/(\tilde{\omega}\sqrt{\theta})=f(N/\sqrt{\theta}, V/\sqrt{\theta}, T_4/\theta)$$

Thus: —

$$\psi/\tilde{\omega}=\frac{P/(\tilde{\omega}\sqrt{\theta})}{N/\sqrt{\theta}}\frac{N_{\max}}{\tau}=f(N/\sqrt{\theta}, V/\sqrt{\theta}, T_4/\theta),$$

At a *fixed* cruise *r.p.m.* and *optimum J.P.T.*: —

$$\psi/\tilde{\omega}=f(V/\sqrt{\theta}, \theta) \qquad . \qquad . \qquad (11)$$

Figure 6 is a graph of $\psi/\tilde{\omega}$ against temperature at 13,600 r.p.m. The slope of the mean line has been taken from the Rolls-Royce brochure of engine performance data. The line is related to the Rolls-Royce powers at 250 knots corrected for auxiliary power off-take by the formula: —

$$P_{RR}=3{\cdot}58\,\psi\frac{N}{N_{\max}} \qquad . \qquad . \qquad (12)$$

A theoretical value for the torquemeter constant is not available, but as the fuel flows are above the Rolls-Royce brochure line (*see* Fig. 4) it is likely that the powers are also high and the true torquemeter constant is higher than 3·58. The operating torque limit has been given as 255 lb./in.² torque pressure in some references and 870 h.p. in others. If these figures can

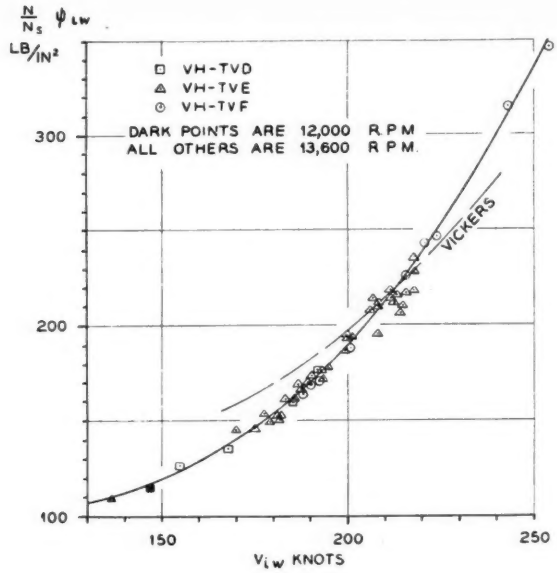



FIGURE 5. Torque-speed relation.

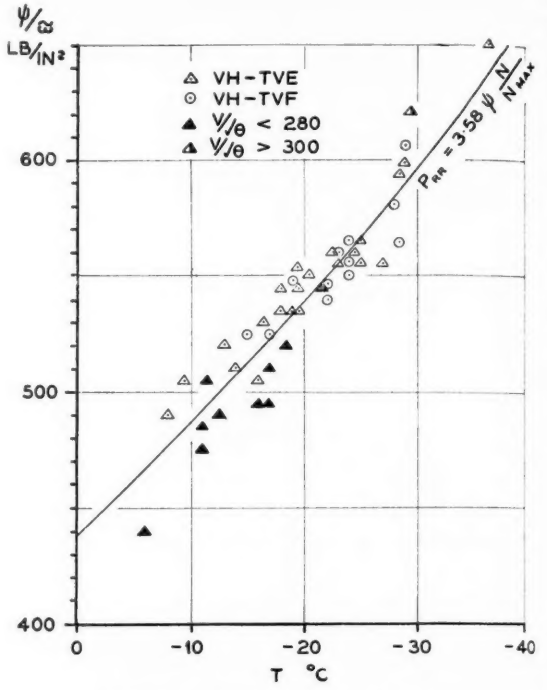



FIGURE 6. Torque pressure, 13,600 r.p.m.

be regarded as consistent, the torquemeter constant must be about 3·64 and the powers about 2 per cent above the brochure. However, knowledge of the constant is not important; Figs. 5 and 6 can be used to determine the performance of the aircraft without reference to it.

The mean line in Fig. 6 takes no account of the effect of $V/\sqrt{\theta}$ on $\psi/\tilde{\omega}$, which is known to be small. To obtain a comparison of the two methods of cruise analysis, a carpet of $V/\sqrt{\theta}$ in terms of $W/\tilde{\omega}$ and temperature was drawn up from the mean lines of Figs. 5 and 6 and compared with a similar carpet drawn directly from the test points in non-dimensional form. A slight difference in the slope of the constant $W/\tilde{\omega}$ lines was apparent. A further examination of the points in Fig. 6 led to the detection of a $V/\sqrt{\theta}$ effect amounting to about one per cent of $\psi/\tilde{\omega}$ per 10 knots of $V/\sqrt{\theta}$. By taking the mean line in Fig. 6 as a $V/\sqrt{\theta}=290$ line and allowing for this small effect at other $V/\sqrt{\theta}$ values, good agreement between the two carpets was obtained. This is shown in Fig. 7.

As a matter of interest, the type of torque-speed curve required to produce Vickers performance data was estimated. For various combinations of altitude, air temperature and aircraft weight, speeds were taken from the Vickers brochure and powers from the Rolls-Royce brochure. The Rolls-Royce powers were then converted to indicated torque pressures, using equation (12), and values of $\psi_{iw}$ and $V_{iw}$ were calculated and plotted. The dotted line in Fig. 5 was the result. It shows quite clearly why better performance figures than the Vickers brochure were achieved at high altitudes (*i.e.* low torque).

The difference in slope between the mean line and the Vickers line indicates that the effective induced drag factor is lower than that assumed by Vickers; in fact, it appears to be less than unity. Possibly the Vickers factor was estimated from descents at low power settings and the slipstream has a marked effect; in the Viscount a large portion of the wing is subjected to slipstream effects. On the other hand, there may be an altitude effect built into the experimental line. Since the points were established at cruise r.p.m. the low torque points are all high altitude ones and the high torque points are low altitude ones; as altitude increases Reynolds number and the power applied to the slipstream both decrease. A variation of torquemeter factor with power could also produce the observed effect.

However, the airline operator is mainly interested in establishing how the aircraft performs; the reasons for any deviations from the classical theory are of secondary importance. The small amount of scatter in Fig. 5 is regarded as ample justification for its use in the preparation of flight planning data.

### 3.3. COMPARISON OF THE TWO METHODS

The alternative method discussed in Section 3.2 is considered preferable for the three following reasons:—

1. The amount of test work required is considerably reduced. Since a day of route flying normally only yields about five level speed tests, and often less if the weather is bad, Fig. 5 can be established in a much shorter time than Fig. 3. Certainly Fig. 6 is required in addition to Fig. 5, but torque readings can be taken instantaneously as soon as the chosen flight conditions are attained and they are not sensitive to slight turbulence; thus a set of torque readings can be

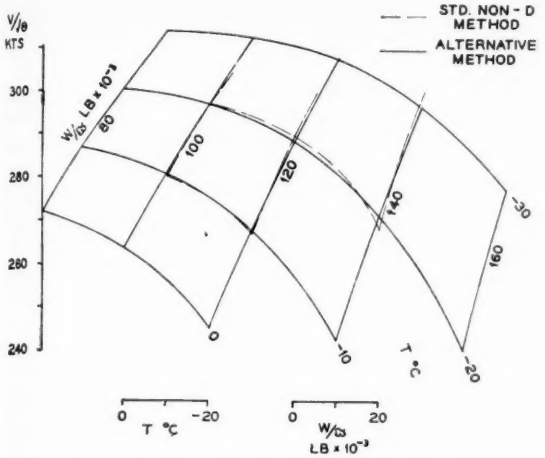



FIGURE 7. $V/\sqrt{\theta}$, $W/\tilde{\omega}$, $T$ carpet, 13,600 r.p.m.

obtained in a fraction of the time required for an equal number of level speeds.

2. The performance standards of the airframe and engines are shown separately, Fig. 5 being an airframe characteristic and Fig. 6 an engine one. If an aircraft is performing badly, the deficiency can be located immediately by taking a set of test readings and pin-pointing them on the two figures. T.A.A. experience has shown that engine deficiencies associated with fuel trimming or J.P.T. instrumentation are the most common cause of poor performance.

3. The estimation of aircraft performance is facilitated when (*a*) the r.p.m. must be reduced to conform with a torque limit or (*b*) full fuel trim has been reached and the J.P.T. is slightly below optimum. In case (*a*) Figs. 5 and 6 are used in conjunction with a curve showing the drop in $\psi/\tilde{\omega}$ with r.p.m., which is roughly 2¼ per cent per hundred r.p.m. for the Dart. In case (*b*) the same figures are used in conjunction with an empirical formula for the drop in torque with J.P.T. Using the term "critical temperature" to denote the air temperature at which full fuel trim is required to maintain optimum J.P.T., the following working rule has been established for the Dart—When air temperature is 10°C. below critical temperature, J.P.T. is 32°C. below its optimum and torque is 9 per cent down.

## 4. The Analysis of Climb Performance

There are two methods of approaching the climb problem which are analogous to the two cruise methods previously discussed. The standard non-dimensional method has been applied in practice and will be fully described; this will be followed by a brief outline of the alternative method.

### 4.1. STANDARD NON-DIMENSIONAL METHOD

From equation (9) of R.Ae.S. Data Sheet RT1/0: —

$$v_c/\sqrt{\theta} = f(N/\sqrt{\theta}, V/\sqrt{\theta}, W/\tilde{\omega}, T_4/\theta).$$

For a *fixed climb r.p.m.* and *optimum J.P.T.*: —

$$v_c/\sqrt{\theta} = f(V/\sqrt{\theta}, W/\tilde{\omega}, \theta).$$

If, in a particular series of tests, the equivalent air speed on climb is varied in proportion to the square root of the aircraft weight: —

$$V_i/\sqrt{\tilde{\omega}} = K(W/\tilde{\omega})^{\frac{1}{2}}$$

where $K$ is constant for that series of tests

but $$V_i/\sqrt{\tilde{\omega}} = V/\sqrt{\theta}$$

so $$V/\sqrt{\theta} = K(W/\tilde{\omega})^{\frac{1}{2}}.$$

Thus the above equation reduces to: —

$$v_c/\sqrt{\theta} = f(K, W/\tilde{\omega}, \theta) \quad . \quad . \quad (13)$$

Climb tests were carried out at three values of $K$ over a range of weights and temperatures. For each climb a graph of $v_c/\sqrt{\theta}$ against $W/\tilde{\omega}$ was produced with the air temperatures marked against the test points as shown in Fig. 8. By picking off values of $v_c/\sqrt{\theta}$ and temperature at chosen values of $W/\tilde{\omega}$ a grid such as Fig. 9 was then drawn up for each value of $K$.

The temperature spread at each value of $W/\tilde{\omega}$ was not very great because the tests were all made in autumn and early winter. It was found, however, that lines of constant $W/\tilde{\omega}$ with gradients obtained from Vickers climb data fitted the points quite well, so Vickers gradients were used throughout. These gradients are values of

$$\left[\frac{\partial(v_c/\sqrt{\theta})}{\partial T}\right]_{W/\tilde{\omega}, K}.$$

Since constant $K$ implies constant lift coefficient, they are not affected by any disagreement over the induced drag factor and depend primarily on the variation of

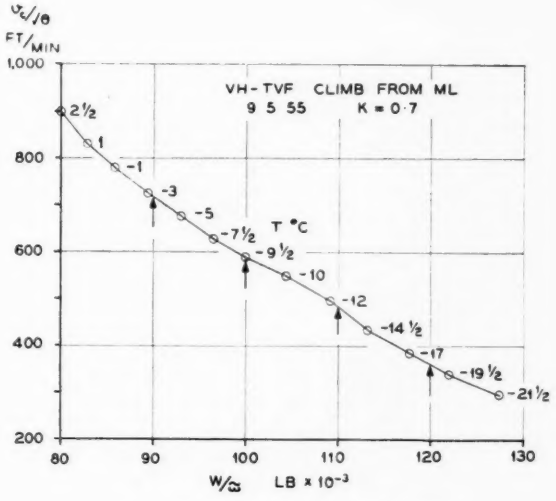



FIGURE 8. Result of typical climb test.

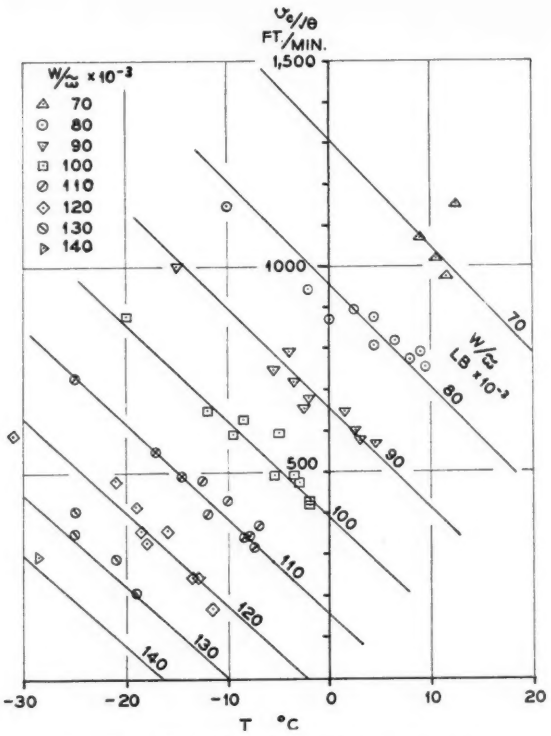



FIGURE 9. Rate of climb, 13,600 r.p.m., $K=0{\cdot}7$.

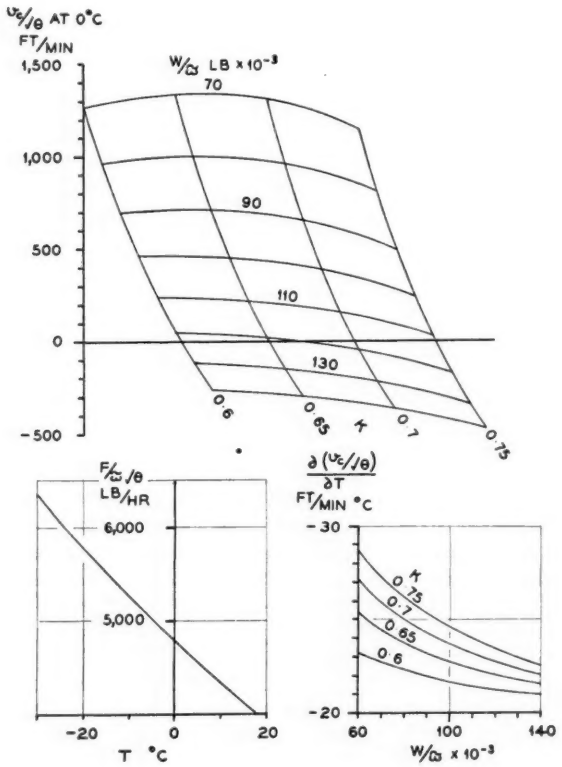



FIGURE 10. Climb carpet, 13,600 r.p.m.

engine power with temperature. It will be recalled that Fig. 6 confirmed the Rolls-Royce temperature effect used by Vickers in their performance estimates.

The intersections of the constant $W/\tilde{\omega}$ lines with the $T=0°C$ line were used to produce Fig. 10, which shows the effects of weight, altitude, temperature and air speed on rate of climb in non-dimensional form. If the gradients of the constant $W/\tilde{\omega}$ lines were slightly incorrect, the 0°C performance would be incorrect in the opposite sense as illustrated in Fig. 11. Thus the errors resulting from the use of Fig. 10 to estimate rates of climb in the working range of temperature would be small.

The climb fuel flow shown in Fig. 10 still conforms with equation (7) but, because of the difference in $V/\sqrt{\theta}$, the mean line is lower than the mean cruise line in Fig. 4. At low temperatures the difference between the two mean lines decreases because the low temperature climb points were obtained at high altitudes where the true air speeds for climb and cruise approach each other.

### 4.2. OUTLINE OF AN ALTERNATIVE METHOD

Adapting the American $P_{iw}V_{iw}$ method to the climb of a turbo-prop aircraft, the cruise equation (9) is replaced by: —

$$550\, m\eta_T\psi_{iw}\frac{N}{N_{\max}}\left(1+\frac{\Delta P}{\eta P}\right)=AV_{iw}^{3}+\frac{B}{V_{iw}}+W_s v_{ciw} \quad . \quad . \quad . \quad (14)$$

where $$v_{ciw}=\frac{v_c\sqrt{\sigma}}{W_R^{1/2}}$$

but $$V_{iw}=V_i\,(\text{ft./sec.})\sqrt{\frac{W_s}{W}}=1{\cdot}69\,K\sqrt{W_s}$$

so, if $\left(1+\frac{\Delta P}{\eta P}\right)$ can again be regarded as constant: —

$$\dot{C}\frac{N}{N_s}\psi_{iw}=A'K^3+\frac{B'}{K}+W_s v_{ciw}$$

where $A'$ $B'$ and $C$ are constants.

or $$v_{ciw}=f\left(K,\frac{N}{N_s}\psi_{iw}\right) \quad . \quad . \quad (15)$$

A check on the variation of propeller efficiency and jet power over the climb range has shown that they are not as constant as they were over the cruise range. However, for the Viscount their variation is still sufficiently small to justify the use of equation (15) in practical performance estimates. To confirm this $v_{ciw}$ was plotted against $\psi_{iw}$ for a series of climbs at $K=0{\cdot}7$ and 13,600 r.p.m. The mean line was straight, as would be expected from equation (14), and the maximum scatter from the mean line was 50 ft./min.

To complete the climb analysis, it would be necessary to produce a carpet of $v_{ciw}$ in terms of $\psi_{iw}$ and $K$ at climb r.p.m. and also a graph of $\psi/\tilde{\omega}$ against temperature for $V/\sqrt{\theta}$ values in the climb range. From these it would be possible either to calculate rates of climb directly or, to produce a rate of climb carpet similar to Fig. 10.

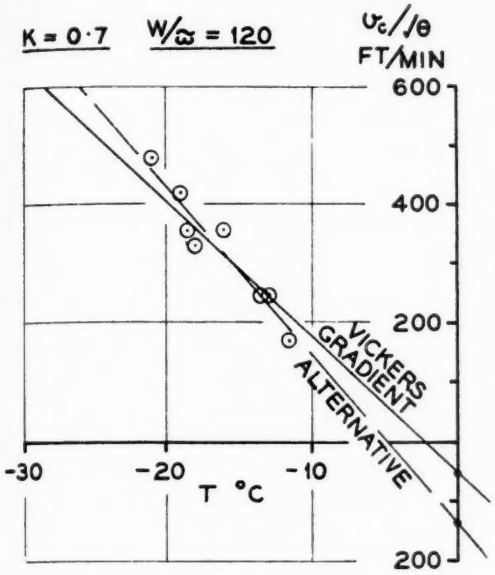



FIGURE 11. Effect of change in gradient.

This method appears to have similar advantages to those discussed in Section 3.3 and is currently being applied to the analysis of the climb performance of the Viscount 756. Results up to the present time are very encouraging and the use of an S.E.P.2 automatic pilot with air speed coupling has had a marked effect in reducing scatter.

## 5. The Analysis of Descent Performance

A theoretical analysis of a descent at a fixed indicated air speed showed that the effects of weight and temperature were very small. An increase in weight increased the drag of the aircraft but at the same time increased the potential energy to be destroyed by that drag during descent. Similarly an increase in temperature increased the drag power $DV$ by increasing the true air speed but simultaneously increased the physical height to be lost when descending from a given pressure altitude. Assuming constant torque and r.p.m., there was no temperature effect on power or fuel flow. When time, fuel and distance were plotted against pressure altitude, the only significant effect of the two variables was a variation in distance caused by the temperature effect on true air speed.

The experimental establishment of descent data therefore resolved itself into plotting time and fuel against pressure altitude for a number of test descents at 200 kts. I.A.S. and determining a mean time line and a mean fuel line. A theoretical correction was made to allow for a reduction in I.A.S. below 6,000 ft. so that the aircraft would enter the circuit at 150 kts. The descent distance in I.S.A. and I.S.A.+20 was estimated from the time graph and presented as a mean true air speed.

To put these approximations into their true perspective it should be stated that the time taken for descent is only about one-third of the climb time and the fuel used is only about one-sixth of the climb fuel.

## 6. The Presentation of Performance Data to the Pilot

Grids of true air speed in terms of altitude and temperature were prepared from Figs. 5 and 6 for various aircraft weights; Fig. 12 shows the type of presentation chosen. Two grids were produced for each weight to avoid the crossing of altitude lines caused by throttling to the torque limit at the lower altitudes. If the ambient air conditions cannot be located on the upper grid the engines must be either torque limited or at full trim and it is necessary to refer to the lower grid.

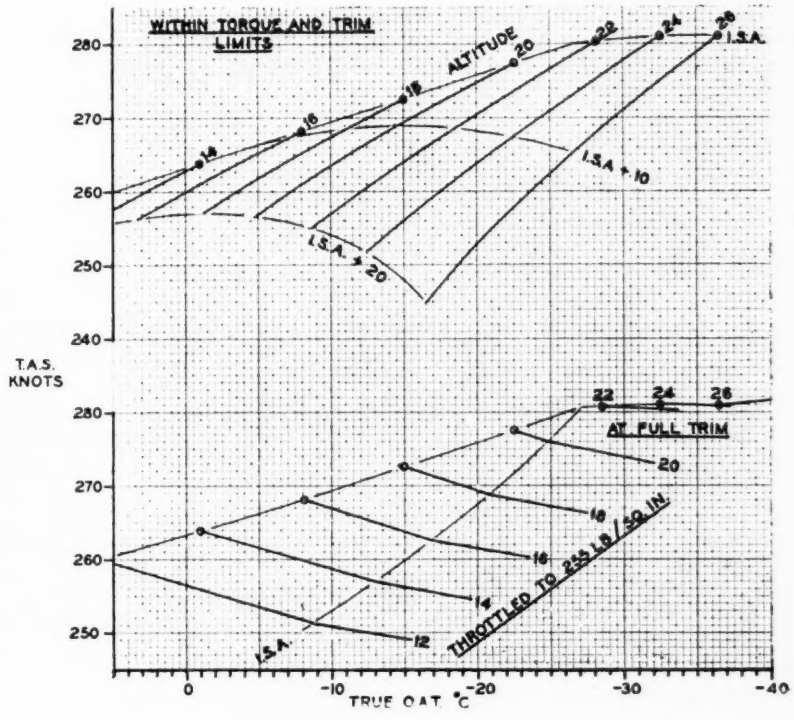



FIGURE 12. True air speed, 50,000 lb., 13,600 r.p.m.

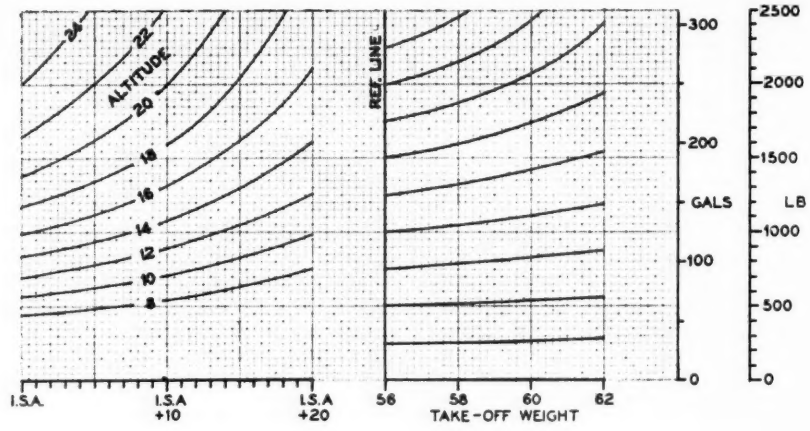



FIGURE 13. Climb fuel 13,600 r.p.m. 175 knots I.A.S.

The virtue of this presentation is that the speed for any odd temperature can be read directly without converting it to the "I.S.A. plus" basis and interpolating between, say, I.S.A.+5 and I.S.A.+10, curves. Grids were produced for a series of weights only 3,000 lb. apart so that the speed variation between grids would only be about 3 knots and for most purposes it would be sufficient to take the nearest weight; thus interpolation should be completely avoided.

A pair of similar grids showing fuel flow were produced from Fig. 4. In this instance there was, of course, no change with weight.

From Fig. 10, climb grids showing time, fuel and mean true air speed to height were prepared, using the type of presentation shown in Fig. 13. This presentation also avoids interpolation. The climbing speeds were chosen after an economic assessment at various weights. The fuel, time and direct operating cost were calculated from the start of climb to a point 200 nautical miles away, using various climbing speeds and adding to each climb an accelerating level cruise beginning from the climbing speed. At the higher weights used on long-range flights, minimum fuel to 200 n.m. was taken as the criterion while at the lower weights minimum cost was considered more important. On this basis 175 knots I.A.S. was chosen as the best overall figure for weights above 56,000 lb. and 165 knots for weights below that figure. A set of grids was prepared for each weight range.

In the absence of weight as a variable, the descent was presented more simply in the form of curves of time, fuel and mean true air speed against altitude.

The charts described above give the pilots climb and cruise performance at 13,600 r.p.m. and descent performance at 11,000 r.p.m. on six quarto sheets which can be used with practically no interpolation. The range of variables covered is:—

| | |
|---|---|
| Weight | 50,000 to 62,000 lb. |
| Altitude | 14,000 to 26,000 ft. |
| Temperature | I.S.A.−5 to I.S.A.+20 |

It has been found that, after some initial resistance, the average pilot soon becomes accustomed to graphical presentation. Furthermore, while small errors may be made due to misreading of scales, the large errors due to looking up the wrong sheet in a set of tables should be eliminated. With the provision of the planning charts described in the next section, the detailed performance charts should seldom be used by T.A.A. pilots. However, it is necessary to have them for long charter flights and they are sometimes useful for checking on the performance of the aircraft. Their occasional use is, of course, one of the strongest arguments for condensing them as far as practicable.

All the performance charts refer to the aircraft with slipper tanks fitted. The effect of removing the tanks is to increase true air speed by about 8 knots. This is regarded as performance bonus on the short range aircraft and no allowance is made for it in flight planning.

## 7. The Preparation and Use of Planning Charts

From the detailed performance charts described in the last section a series of large graphs of flight time

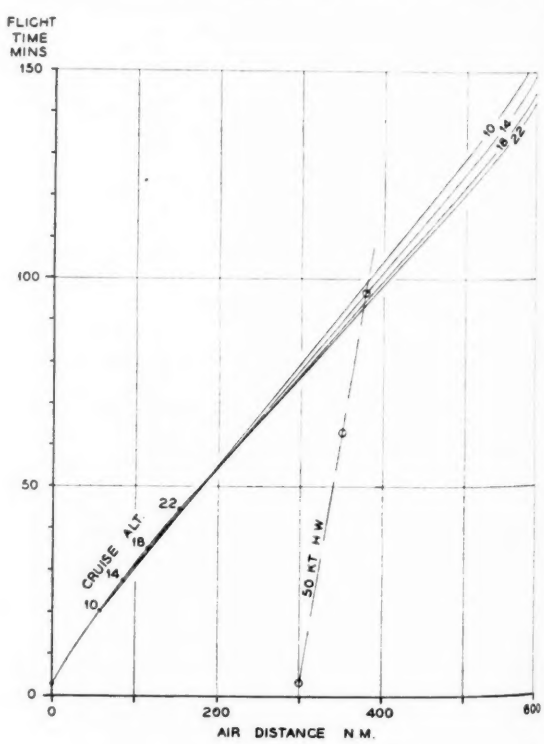



FIGURE 14. Flight time in I.S.A.

and flight fuel against air distance were prepared. They were drawn for three different temperature régimes, the I.S.A. time graph in Fig. 14 being a typical example, and were composed of climb, cruise and descent plus allowances for turning on to course and circuiting at the destination. The assumed time allowance was 3 minutes, so a straight line starting from the 300 nautical mile, 3 minute point and passing through the 350 nautical mile, 63 minute point represents a flight of 300 *ground* nautical miles against a 50 knot headwind. Such a line is shown in Fig. 14 and its intersection with the 14,000 ft. line gives the air distance and flight time for a cruising altitude of 14,000 ft. in I.S.A.; the flight fuel can be found by entering the I.S.A. fuel graph with the air distance found from the time graph.

The route planning charts, of which Fig. 1 is a typical example, were drawn up from the time and fuel graphs, using the foregoing method to estimate wind effects. The time and fuel graphs were about one foot square and the average route planning chart for a 400 nautical mile stage was derived from a small section of each graph about two inches square. Therefore, to obtain regular smooth curves in the planning charts, it was necessary to draw the graphs with extreme care. Millimetre graph paper was used and an attempt was made to work to the nearest fifth of a millimetre.

The schedule time intervals in the top left-hand corner of each planning chart were obtained by plotting a time-distance graph for the appropriate stage length in typical conditions (18,000 ft., I.S.A. + 10, zero wind) and factoring the times between check points by $\frac{\text{schedule flight time}}{\text{typical flight time}}$.

When making out his flight plan, the pilot reads the flight time and flight fuel from the chart and, using his logarithmic computer, factors the schedule time intervals by $\frac{\text{actual flight time}}{\text{schedule flight time}}$.

He does not need to worry about the detailed breakdown of the flight into climb, cruise and descent or even to know what his cruising speed and consumption will be. However, as mentioned in Section 6, they are available to him if he wants them.

To cater for short flights on routes for which no route planning charts are available, a series of general planning charts such as Fig. 15 were also drawn up from the time and fuel graphs. Eight general planning charts were prepared to show flight time and flight fuel for four different cruise altitudes. Each one covers stage distances up to 500 nautical miles over a range of winds and air temperatures; however, for convenience of presentation, Fig. 15 was abbreviated to 300 nautical miles.

## 8. Operation for Best Economy

On Australian east coast operations, where range is not critical, it is desirable to select the cruising altitude to give the minimum direct operating cost per stage. For two typical stage distances, 400 and 700 nautical miles, direct operating cost was calculated for various temperatures, altitudes and wind gradients. Graphs were then produced to show the altitude for minimum direct operating cost in terms of wind gradient for three temperature régimes. The 400 and 700 nautical mile graphs are similar in shape and, for practical purposes, the following rule can be regarded as an acceptable approximation to either of them: —

> "In tailwind gradients and headwind gradients up to 2 knots/1,000 ft. cruise as high as practicable; in headwind gradients above 2 knots/1,000 ft. cruise at the torque limit altitude."

The highest practicable altitude is taken as the

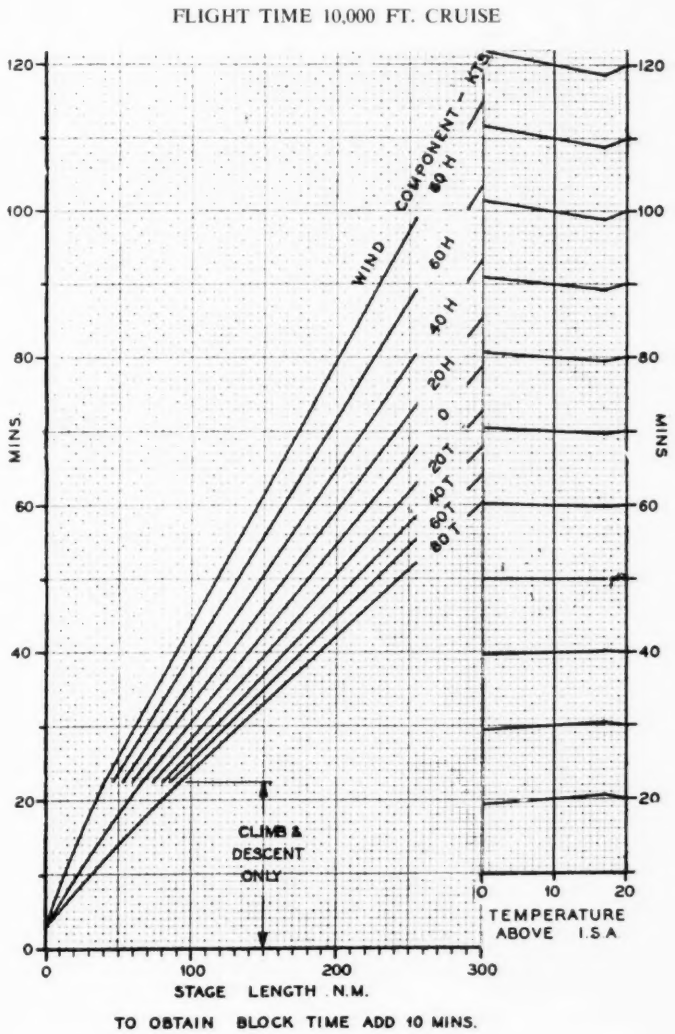



FIGURE 15. Typical general planning chart.

maximum quadrantal height which can be reached by climbing for one hour. A chart of "Altitude after 60 minutes climb" in terms of weight and temperature is provided and the pilot selects the nearest quadrantal height below the altitude he obtains from the chart. An overall maximum of 25,000 ft. is laid down to maintain reasonable cabin comfort.

The torque limit altitude is very sensitive to the standard of the engines. As mentioned earlier, they vary in power and fuel flow over a wider range than piston engines. Average values of torque limit altitude for the Dart 506 engine are 21,000 ft. in I.S.A. and 15,000 ft. in I.S.A.+10. An overall minimum of 14,000 ft. is laid down to avoid turbulence in summer time. It is uneconomic to fly lower than the torque limit altitude because throttling back to maintain the limiting torque increases flight time excessively and this has detrimental effect on cost which far outweighs the slight fuel saving.

This cruise procedure was put into operation at the end of April 1956 and so far only two months' operational statistics have been compiled since its inception. They indicate an increase of about 3 per cent in block miles per lb. with a loss of about ½ per cent in block speed; this should result in a saving of over £2,000 per annum per aircraft if the present figures are sustained. However, operational statistics vary considerably from month to month as the result of weather, changes in the route pattern and withdrawal of aircraft for crew training, so two months' figures cannot be regarded as a certain basis for future estimates.

## 9. The Long Range Cruising Technique

On the 1,200 nautical mile Adelaide-Perth stage, the constant incidence or climbing cruise technique is used. This means that the aircraft is flown at an indicated air speed and allowed to find its own altitude, rather than being flown at an altitude. The indicated air speed is

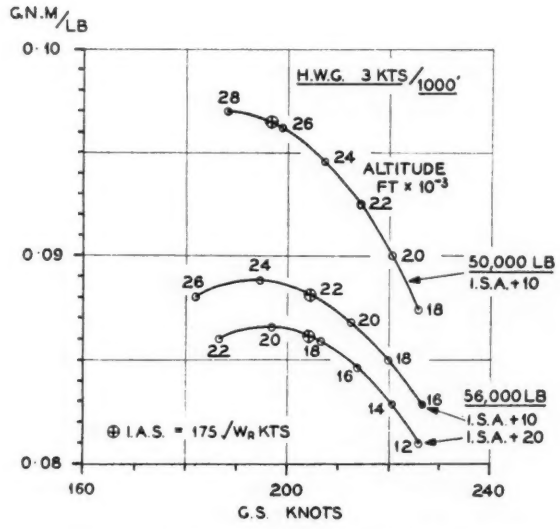



FIGURE 16. Specific ground range in headwind gradient.

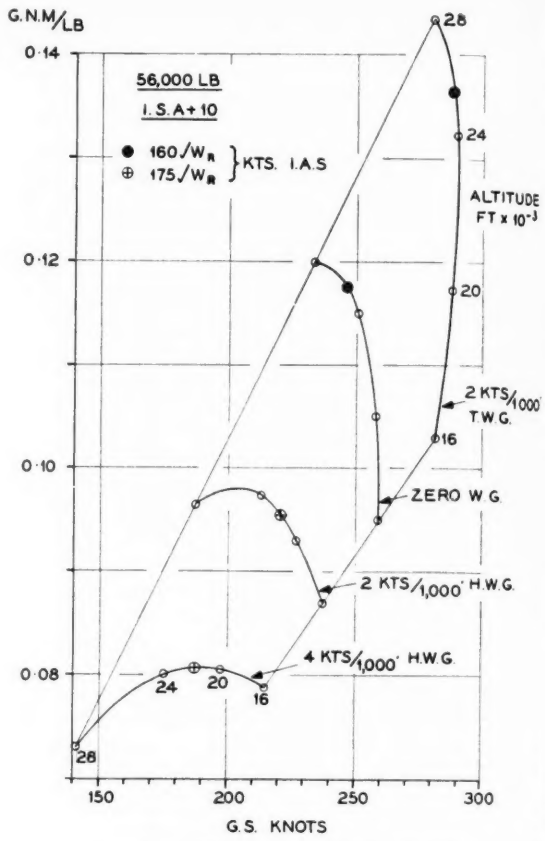



FIGURE 17. Effect of wind gradient on specific ground range.

reduced as the aircraft becomes lighter to keep it in proportion to the square root of the aircraft weight: thus the wing-incidence is kept constant and the aircraft gradually climbs.

Figure 16 shows the variation of ground nautical miles per lb. of fuel and ground speed with altitude in a fixed wind condition, namely a 3 knot/1,000 ft. headwind gradient which is typical of the Adelaide-Perth stage in the critical season. For long range cruising it is desirable to operate on the right-hand side of the maximum ground nautical miles per lb. point. For example, at 56,000 lb. in I.S.A.+10 the maximum is at 24,000 ft., but by cruising at 22,000 ft. the ground speed can be increased by 10 knots with a reduction of only ½ per cent in range. At lower altitudes the reduction in range becomes more severe and the gain in speed smaller, so an altitude of about 22,000 ft. is the best compromise for that particular weight-temperature combination.

The other curves in Fig. 16 show that as weight and temperature are varied the optimum point moves to a different altitude. However, if the incidence of the aircraft is kept the same, it changes its altitude to maintain a similar position relative to maximum ground nautical miles per lb. This is illustrated by the three crossed circles in Fig. 16, which are points of the same

incidence. A great advantage of the constant incidence cruise is that it does not rely on meteorological temperature forecasts. If the aircraft is flown at the optimum incidence and the temperature conditions are vastly different from those forecast, it still settles down in the desired position relative to maximum ground nautical miles per lb., although at a different altitude from that planned.

Figure 16 is concerned solely with a fixed wind condition. If the wind gradient changes, the optimum altitude and the optimum incidence both change. This is shown in Fig. 17, which has been drawn up for a fixed weight and temperature with a variety of wind gradients. It would not be practicable to operate on a sliding scale of indicated air speed against wind gradient, so two procedures have been evolved; one, called the high speed climbing cruise, is used in strong headwind gradients, and the other, the low speed climbing cruise, is used in light headwind gradients and tailwind gradients. The operating points for these procedures are shown in Fig. 17 by crossed circles and dark spots respectively. A further improvement could be achieved in strong tailwind gradients by using a lower indicated air speed but, in practice, the aircraft would be too difficult to handle.

For planning the constant incidence cruise, tables of the type shown in Fig. 18 are provided. This particular table refers to the high speed climbing cruise, for which I.A.S. $= 175\sqrt{W_R}$ knots. The indicated air speeds in the lower right-hand corner represent a practical approximation to this rule and the figures in the main body of the table are averages for the four 300 nautical mile sectors, assuming a typical fall-off in weight as ground distance increases; the actual rate of change of weight with distance must, of course, depend on the wind conditions of the day. It will be noticed that altitudes above the 25,000 ft. limit are called for on cold days. Operation at these higher altitudes is only permitted if they are necessary to avoid an intermediate landing for refuelling. If conditions are not critical, the figures in the lower left-hand corner are used.

As the climbing cruise procedures are only used on critical stages, the tables are based on a minimum standard of Viscount performance rather than the performance of the average aircraft.

## 10. Present Trends in Performance

The tests which provided the data for the analysis of Viscount 720 performance were largely concentrated

HIGH SPEED CLIMBING CRUISE 13,600 R.P.M.

| 62,000 T.O.W. | | TOC-300 | 300-600 | 600-900 | 900-1200 | Nautical miles |
|---|---|---|---|---|---|---|
| 59,000 T.O.W. | | Nautical miles | TOC-300 | 300-600 | 600-900 | 900-1200 |
| I.S.A. | Altitude | 22.5 | 24.5 | 26.5 | 28.5 | 31.0 |
| | T.A.S. | 255 | 260 | 260 | 265 | 265 |
| | Fuel Flow | 2430 | 2310 | 2180 | 2020 | 1890 |
| + 5 | Altitude | 21.0 | 23.0 | 25.0 | 27.0 | 29.5 |
| | T.A.S. | 250 | 255 | 255 | 260 | 260 |
| | Fuel Flow | 2470 | 2350 | 2220 | 2060 | 1930 |
| + 10 | Altitude | 19.0 | 21.0 | 23.0 | 25.0 | 27.5 |
| | T.A.S. | 245 | 250 | 250 | 255 | 255 |
| | Fuel Flow | 2510 | 2390 | 2260 | 2100 | 1970 |
| + 15 | Altitude | 17.0 | 19.0 | 21.0 | 23.0 | 25.5 |
| | T.A.S. | 240 | 245 | 245 | 250 | 250 |
| | Fuel Flow | 2550 | 2430 | 2300 | 2140 | 2010 |
| + 20 | Altitude | 15.0 | 17.0 | 19.0 | 21.0 | 23.5 |
| | T.A.S. | 235 | 240 | 240 | 245 | 245 |
| | Fuel Flow | 2580 | 2460 | 2330 | 2170 | 2040 |

25,000 ft. Cruise

| | T.A.S. | Fuel Flow |
|---|---|---|
| I.S.A. | 270 | 2290 |
| + 5 | 265 | 2210 |
| + 10 | 260 | 2130 |

CLIMB: 175 kts I.A.S. for 1 hour. 220 kts T.A.S. This brings the aircraft to the stabilised altitude. It then commences the cruise at the same I.A.S.

DESCENT: 200 kts I.A.S. for 20 mins. 255 kts T.A.S.

FLIGHT FUEL = Cruise + 3700 lb.

FLIGHT TIME = Cruise + 85 mins.

NOTE: All figures in the table above are averages over the range intervals.

CRUISE SPEED

| Weight | I.A.S. |
|---|---|
| 60 to 55 | 175 |
| 55 to 52 | 170 |
| 52 to 49 | 165 |
| Below 49 | 160 |

FIGURE 18. Climbing cruise chart for headwind gradients.

on two aircraft, VH-TVE and VH-TVF. Both of these aircraft were fitted with 506 engines assembled at Derby and there was no significant difference between their standards of performance.

Some further tests were made on aircraft fitted with engines that had seen some service as 505 series and later been converted to 506 by Rolls-Royce, Australia. After the correction of certain initial defects in J.P.T. indication and trimming linkage, which were mainly the result of the inexperience of maintenance crews who installed them, the converted engines were found to be, on the average, "hot" ones. A "hot" turbo-prop engine has a high J.P.T. under test conditions at a standard fuel flow and r.p.m.; thus when trimmed to a standard J.P.T. it has a low fuel flow and low power output. The converted engines were also found to be more variable in their performance than the initial batch of 506 engines; the best of them were as good as an average 506, but some of them were as much as 10 per cent low in torque. This does not imply that the engines were outside the manufacturer's guarantee. The guarantee takes the form of a guaranteed power at a certain fuel flow and hot engines, which are restricted to a low power output by the J.P.T. limit, are usually found to have a low fuel flow.

When VH-TVG arrived, performance tests showed that it was about 4 knots faster than the earlier aircraft and most of the improvement was attributable to increased engine torque; one engine was particularly cold and consistently indicated a torque 10 per cent above average. This good performance was maintained throughout the life of the initial set of engines.

The history of individual engines has been closely followed by the Power-Plant Engineer and it has been found that the initial standard of an engine is no indication of the way it will behave after overhaul; a hot engine may become an average or cold one and *vice-versa*. All this suggests that the J.P.T. of a turbo-prop engine under test conditions, which determines its power output under operating conditions, is very sensitive to small differences in assembly procedure. Possibly turbine clearances and small changes in blade contour due to wear have quite a large effect, although all dimensions are within the tolerances laid down. In some cases, engines have shown a marked deterioration during service and it has been possible to restore their power by replacing the J.P.T. thermocouples; it appears that these can develop faults under operating conditions which do not show up in an electrical test in the cold condition.

In view of the fact that the engines in VH-TVE and VH-TVF were drawing more fuel and presumably giving more power than indicated by the manufacturer's brochure, and that those in VH-TVG showed a further increase in fuel flow and power output, it seems likely that the assembly techniques or inspection standards are continually improving. It may seem strange to those experienced in piston engines to read remarks by an operator complimenting an engine manufacturer on an observed increase in fuel flow. The point to be remembered is that specific consumption is guaranteed and, if an increase of 5 per cent in both power and fuel flow can be achieved at a given altitude, r.p.m. and J.P.T., the aircraft will cruise 1,500 ft. higher on the long range climbing cruise. This height increase at a fixed indicated air speed increases true air speed by $2\frac{1}{2}$ per cent and reduces fuel flow by $4\frac{1}{2}$ per cent so the net effect is a $\frac{1}{2}$ per cent increase in fuel flow and a 2 per cent increase in air miles per lb. Furthermore, the torque increase obtained in a cold engine is usually greater than the fuel flow increase, so the net effect is likely to be even more beneficial than the above figures indicate.

## 11. Concluding Remarks

The test observation and performance analysis work described in this paper occupied the author and his assistant for a period of seven months. The subsequent calculation of the planning charts and the development of the best economy and maximum range cruise techniques absorbed the efforts of the author only for a further four months. However, the methods were being developed as the project proceeded and much effort was wasted on trying out various approaches to the problem and on recording and reducing a greater number of observations than were finally required for the "alternative" method of analysis. A similar job on another turbo-prop aircraft could probably be carried out by two engineers in about five months.

A project of this magnitude should not seem a heavy financial burden on an airline operating a reasonable fleet of modern aircraft when it is considered that the cost of ten man-months of technical labour is only equal to the cost of operating one aircraft for a day and a half. There should be no additional flying costs because all the observations can be taken on scheduled passenger flights or routine test flights. In view of the time saved by the use of route planning charts, and the possible savings associated with the introduction of a best economy technique, a strong case can be made for such a performance study in any airline operating turbine aircraft, whether turbo-prop or turbo-jet. The argument that the need did not exist in the old days is irrelevant; as mentioned earlier, the performance of piston-engined aircraft is much less complex and relatively insensitive to altitude and temperature effects.

ACKNOWLEDGMENTS

The author wishes to express his appreciation to J. A. Walshe, Assistant Engineer (Performance), for his continuing assistance in the work described, and also to the numerous Viscount pilots whose co-operation was essential to the success of the tests. Particular mention should be made of the persistent efforts of Captain J. a'B. P. Boyd, D.F.C., in establishing the most difficult level speeds in the region of the minimum drag speed. Thanks are due also to the Management of Trans-Australia Airlines for their permission to publish this work, and to D. House for his careful reproduction of the charts and figures.

EDITOR'S NOTE:—*Publication of Mr. Baxter's paper was delayed to give Rolls-Royce Ltd. and Vickers-Armstrongs an opportunity to comment.*

# *Comment From*

D. J. LAMBERT

*(Chief Development Engineer (Civil) Vickers-Armstrongs (Aircraft) Ltd.)*

MR. BAXTER'S PAPER is most interesting and as far as is known, represents the first published airline analysis of turbo-prop operational performance on a reasonable scale. He is to be congratulated on the extent of his analysis and his method of approach to the several new problems which faced T.A.A. with the introduction of Viscounts. It must be remembered, however, that the T.A.A. operation is unique in its combination of a high frequency domestic short medium range network with one relatively low frequency extreme range (for the Viscount) route. T.A.A. is fortunate in being able, at least at the moment, to apply the cruise climb technique on this long stage with relatively unrestrictive A.T.C. limitations. This is emphasised in Section 4.2 which sets forth the advantages of an auto-pilot speed lock for this type of operation. It is interesting to note that the first Viscount 756, VH-TVH was the first Viscount to be fitted with such a device in association with the S.E.P.2 auto-pilot, and undoubtedly the requirements of the Adelaide-Perth sector were strong in T.A.A.'s mind in making this choice. Of course, many operators have to conform with very rigid A.T.C. requirements for fixed altitude operation and often with a poor choice of available altitudes. In their cases, the requirement is very definitely for a height lock which allows E.A.S. to increase as weight decreases through fuel burn off. While this is not theoretically the most economic technique on medium ranges in countries where fuel is expensive and labour cheap, it has much to commend it where fuel is cheap and labour expensive.

Incidentally, Mr. Baxter's point at the beginning of Section 10 about maintaining constant incidence, is clearly sound but it is for debate whether the benefit to be obtained by regularly re-setting the speed lock to reduce E.A.S. as fuel is burned is worth the added crew work load. It is probable that on such a medium range operation the setting of a suitable speed to give the correct mean incidence for the cruise is near enough.

Is Mr. Baxter correct in implying that reasonable cabin comfort in a Viscount is achieved only if the aircraft is held below 25,000 ft. (Section 9)? At this height the working cabin differential of 6·5 p.s.i. gives a cabin altitude of 5,500 ft. Certainly many other Viscount operators operate up to 30,000 ft. as and when it is expedient and the aircraft is cleared for operation up to 33,000 ft.

Another point which perhaps should be drawn to the reader's attention, is that methods of performance reduction which are suitable for airline operational purposes on a particular type of series, are seldom suitable for use by a manufacturer in performance prediction, and the production of Flight Planning Tables, climb and cruise performance, and so on, for general world wide use. In these cases I feel that analysis on the basis of basic airframe and engine data is essential.

The opinions expressed here are purely personal.

*Received January* 1957.

# *Mr. Baxter's Reply*

As presumed by Mr. Lambert the air speed lock was specified to cater for the climbing cruise on the long-range Adelaide-Perth route. However, since it has been put into service, it has been found to be a far more valuable device than was ever anticipated.

On the East Coast routes of about 400 nautical miles, where conventional flight procedures are used, the air speed lock is engaged as soon as climbing speed is attained after take-off. The aircraft is then climbed by the auto-pilot for about 40 to 50 minutes until cruising altitude is reached, when the air speed lock is disengaged and the altitude lock engaged. After overshooting slightly, the aircraft settles down at the cruising altitude and remains there under barometric control until the descent point is reached some 40 minutes later. The altitude lock is then disengaged and the nose slightly depressed by the auto-pilot pitch control. When descent speed is attained the air speed lock is again engaged and, as the throttles are slowly drawn back, the auto-pilot eases the aircraft into the descent and maintains the chosen speed down to the altitude where reduction to approach speed becomes necessary. Thus, apart from its value on the climbing cruise and on climb performance tests, the air speed lock is used more than the altitude lock on normal short range flights where the climbing cruise is neither appropriate nor permissible.

Mr. Lambert's comment on the effect of the national cost structure on cruising technique is interesting and had not previously occurred to the author. In Australia the price of turbine fuel is comparable with that in England but higher than in U.S.A., while labour is more expensive than in England but cheaper than in U.S.A.; the cost ratio would therefore be intermediate between the two extremes.

It will be realised, of course, that this factor can

*Received March 1957.*

only influence the technique for best cost economy. The climbing cruise is still the best technique for fuel economy or maximum range. As shown in the lower right hand corner of Fig. 18, the indicated air speed is only varied at four points on the 6-hour stage from Adelaide to Perth; on three occasions it is reduced by five knots and finally it is increased for descent. The work load is therefore negligible. If there should be a move at some future date to base aircraft and component overhaul lives and air crew commitments on number of flights rather than number of hours flown, as has been suggested in some quarters, it is interesting to note that the minimum cost technique would become identical with the maximum range technique.

In regard to the 25,000 ft. altitude limit, it should be pointed out that T.A.A. operates in an extremely competitive field. Four airlines, all with modern aircraft, compete on the main routes and two of these operate to Perth. The Viscount has been successfully sold to the public on the basis that it is the fastest, most comfortable and most highly pressurised passenger aircraft in the country and it is important not to break faith with the public by subjecting them to cabin altitudes similar to those experienced on aircraft such as the D.C.-4. The Management of T.A.A. has therefore set a cabin comfort limit of 6,000 ft.

In conclusion it is perhaps worth mentioning that the cruise and climb performance of the Viscount 756 aircraft with Dart 510 engines has now been measured and analysed by the methods described in Sections 3.2 and 4.2. Experimental scatter has been reduced considerably by the use of the air speed and altitude locks of the S.E.P.2 auto-pilot and a 20-turn r.p.m. indicator which can be plugged into the output of any of the four tachometer generators. Greater success has been achieved in isolating the $V/\sqrt{\theta}$ effect on $\psi/\tilde{\omega}$ from the temperature or $N/\sqrt{\theta}$ effect and it has been found advisable to use equation (15) in the form:—

$$v_{ciw} = f\left(K, \eta \frac{N}{N_s} \psi_{iw}\right)$$

For a given engine and propeller combination:—

$$\eta = f(V/\sqrt{\theta}, N/\sqrt{\theta})$$

so, for a given r.p.m., $\eta$ can be plotted against $V/\sqrt{\theta}$ and temperature. Having such a plotting, it is easy to calculate

$$\eta \frac{N}{N_s} \psi_{iw}$$

for each of the test points and full allowance can thus be made for variations in propeller efficiency during the climb.

# Ram-Jets*

by

R. R. JAMISON, Ph.D., F.R.Ae.S.

*(Assistant Chief Engineer, Ram-jets, Bristol Aero-Engines Ltd.)*

## Introduction

Ram-jets in Great Britain have, until now, been associated with Guided Missiles and, for this reason, tight security regulations have been in force. In fact, it is only recently that it has been possible to talk about ram-jets at all. Even now, quite a number of features in these engines are classified and, for this reason, some portions of this paper may appear perhaps a little thin and inconclusive, but I have done my best to discuss the subject as fully as possible.

It is now generally known that the work of the Bristol Company has led to the adoption of the Thor ram-jet engine for production by the Ministry of Supply but security restrictions remain and in this lecture I have drawn upon general experience and thoughts in this field and avoided giving information directly related to a particular engine. In these circumstances, of course, the choice of any operating condition for the purpose of giving form to the lecture has had to be a purely arbitrary one.

## General Description

It is necessary, first of all, to say just what a ram-jet is. The first point to make is that it is a form of jet engine in the same general class as a turbo-jet. It is an air-breathing engine which derives thrust by compressing air, heating it and expanding it through a propelling nozzle. It differs from the turbo-jet in its dependence purely on its forward speed for the compression of the air. It can, in fact, be called a "straight line" engine in which the relative motion between the air and the components takes place in a straight line instead of as a rotary motion, as found in the turbo-jet. This means that we are freed from the very high stresses involved in the high speed rotating machinery of the turbo-jet. The essential factor, therefore, is that the ram-jet depends upon forward speed for compression. The speed has thus a direct effect on the compression ratio, but at the same time it is a simple, light and cheap power plant, to such an extent that it has attractions even where its fuel economy may look inferior. In the subsonic field ram-jet consumptions are relatively very high—of the order of six to ten pounds of fuel per hour per pound of thrust. Nonetheless, the subsonic ram-jet has applications where its lightness and low cost outweigh the consumption factor. Examples of this are in a target drone aircraft for high subsonic speed and in helicopter tip drives. The ram-jet can be applied for the latter purpose either for a short range light helicopter for military use, or as boost engines on the longer range helicopter driven by other means. However it is primarily in the supersonic field that the ram-jet finds application, because it is here that it is competitive thermodynamically with other air-breathing engines. Hence, and because that is the work which we have mostly done, the supersonic case will be considered.

Figure 1 illustrates the main features of a supersonic ram-jet operating at a Mach number of 2. The curves on this diagram show how the principal variables of velocity, pressure and temperature behave in the passage of the air stream through the ram-jet duct.

For the moment, an engine of fixed geometry is being considered, because that has up to the present time been our experience and, in any case, makes the subject more manageable. However, variable geometry will be touched on in discussing intake design.

Consider the features governing the behaviour of the ram-jet engine. The most important point to consider arises from the fact that supersonic ram-jet engines in general have a choked propelling nozzle. That is to say, the flow attains the speed of sound in the throat of the propelling nozzle. If, then, any point in the subsonic flow system upstream of the throat is considered, the Mach number at such a point is decided by the ratio of area to the throat area and the ratio of the temperature to the temperature in the throat, so that for a given ram-jet the gas Mach number is defined by the temperature ratio between the point in question and the nozzle throat. Thus, if the exit from the intake diffuser is considered, the Mach number at this point is decided by the ratio of the total temperature in the intake to the flame temperature in the nozzle, and this Mach number has to be reconciled with the Mach number arising after the air has passed through the intake shock system. In other words, the normal shock in the diffuser must position itself to satisfy the downstream condition. The temperature ratio can be varied either by varying the fuel supply and, therefore, the flame temperature, or by varying the intake air temperature, which is a function both of the altitude and forward speed. As the temperature ratio is increased, the Mach number in the diffuser exit falls, and this causes the normal shock to be driven towards the mouth of the intake. In the diagram, the normal shock is shown downstream of the intake lip. This is called a supercritical condition. As the temperature ratio rises, the shock will be driven forward until it is actually on the intake lip. This is called the

*A lecture given to the Derby Branch of the Society on 5th November, 1956.

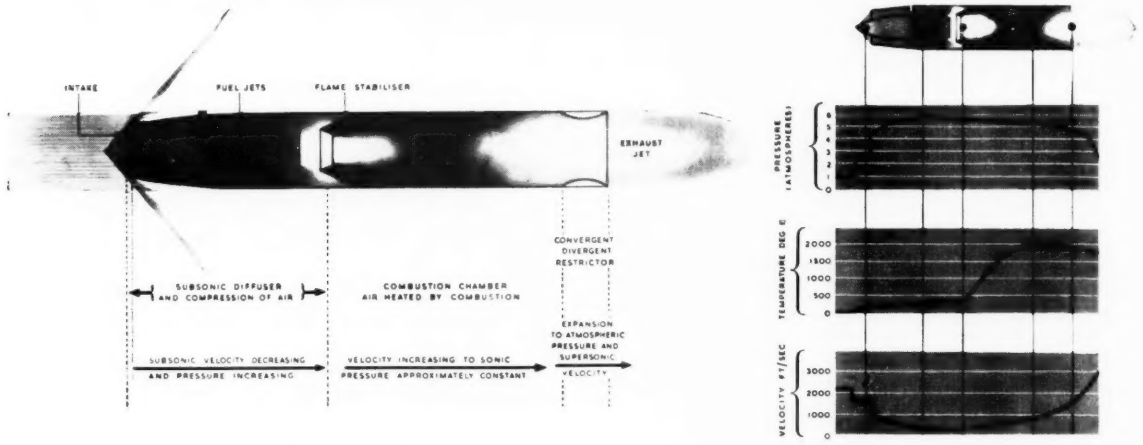



FIGURE 1. Operation of a ram-jet engine (at a Mach number of 2).

critical condition, and represents in general the best pressure recovery point. Further rise in temperature ratio forces the shock out of the intake, causing spillage of a subsonic air stream round the intake lip. This is a subcritical regime.

Figure 2 shows the variation of the diffuser exit Mach number with the temperature ratio for a typical ram-jet engine flying at sea level and in the stratosphere.

In Fig. 3 for comparison a plot is given of the typical diffuser exit Mach number at the design points of a family of ram-jets for the range of Mach numbers from 1 to 4·5. These engines were optimised from a consumption aspect and it will be seen that the diffuser exit Mach number is lower than those shown in the previous Figure at a corresponding flight Mach number of 2, for an engine biased towards high thrust. In this family there is a considerable fall in the diffuser Mach number above free flight speeds corresponding to $M=2$, which shows that combustion conditions are becoming easier at high speeds, in respect of engine pressure, internal velocities and temperatures.

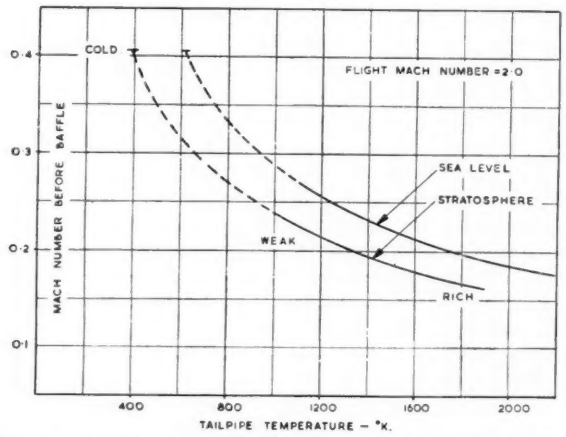



FIGURE 2. Variation of diffuser exit Mach number with temperature ratio for a ram-jet at sea level and in the stratosphere.

## General Consideration of the Role of a Ram-Jet Engine

Having outlined roughly what is meant by a ram-jet engine, the field of application for engines of this type can be discussed. As a ram-jet uses ram for compression, let us see what sort of temperatures and pressures it realises.

Table 1 gives the air stagnation temperatures which would be expected when flying in the stratosphere at Mach numbers ranging from 1 to 6.

It will be seen from this Table that there would be no serious embarrassment from a structural viewpoint until $M=4$ is reached at 640°C. At $M=5$ (1,020°C.) the stagnation temperature has risen to a value where high temperature alloys are losing their strength, and at $M=6$ (1,500°C.) the melting point of most engineering alloys has been reached. Thus flight at these higher speeds would involve quite elaborate cooling means, and would only be practicable at very high altitudes.

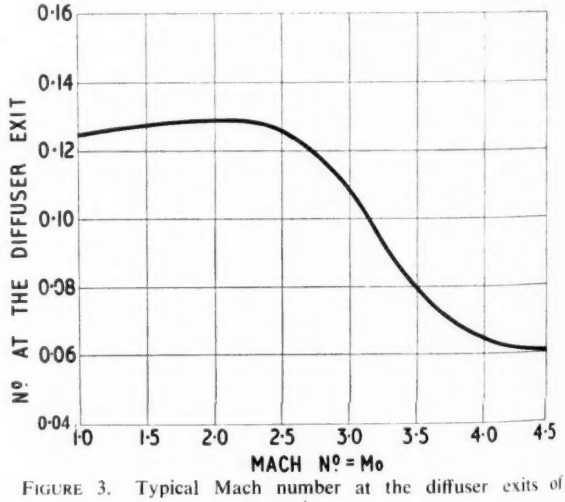



FIGURE 3. Typical Mach number at the diffuser exits of ram-jets.

TABLE I.

AIR STAGNATION TEMPERATURE IN THE STRATOSPHERE

| *Mach number* | *Ambient static temperature °C* | *Air stagnation temperature °C* |
|---|---|---|
| 1·0 | −56.5 | −13 |
| 1·5 | −56.5 | 41 |
| 2·0 | −56.5 | 117 |
| 2·5 | −56.5 | 214 |
| 3·0 | −56.5 | 333 |
| 3·5 | −56.5 | 474 |
| 4·0 | −56.5 | 636 |
| 4·5 | −56.5 | 820 |
| 5·0 | −56.5 | 1,024 |
| 6·0 | −56.5 | 1,502 |

Compression ratios are shown in Fig. 4 where the intake pressure recovery has been plotted against Mach numbers for a variety of intakes. The top line shows the maximum possible pressure recovery, assuming no losses. The line beneath this gives the recovery which would be expected from an isentropic cone, with a normal shock introduced to limit the change of stream direction to a practicable value. This is followed by a curve allowing for subsonic losses and, below this, drawn as a dotted line, is the "practical" curve of intake recoveries, which has been used for the calculations of engine performance used for the subsequent discussion. Further curves are shown for a three-shock, two-shock and a Pitot intake.

It appears, on first looking at these graphs, that the differences between intake performance are not very great, but it is misleading because, in order to encompass the great range of pressure ratios encountered at high Mach numbers, the graph has been plotted on a logarithmic scale. It is worth commenting that the pressure recoveries expected from a Pitot intake at a Mach number of 4·5 would be about 27 atmospheres, compared with roughly 100 atmospheres for an isentropic cone type of intake. It is evident from this diagram that, above a flight Mach number of 2, the ram-jet compression ratios are comparable with, or much greater than, the currently accepted values of turbo-jets. This gives some indication of their likely fields of application.

One way of looking at this can be seen from Fig. 5 which shows possible operating regions as seen in America: the turbo-jet in this case is shown operating up to a Mach number of 2·5 and a height of 80,000 ft. and the ram-jet extending the field to a Mach number of 4·5 and a height of 100,000 ft. Broadly speaking, it appears that the left hand, upper portions, of the two loops reflect engine operating limits, while the right hand, lower portions, are governed by aircraft limitations. These loops give a general appraisal of the relative roles of ram-jets and turbo-jets in supersonic flight, but are, perhaps, a bit too cut and dried. For example, the turbo-jet can be considered applicable to a higher Mach number than 2·5 as shown in the diagram.

This subject can be studied in more detail with the help of curves which have been prepared showing

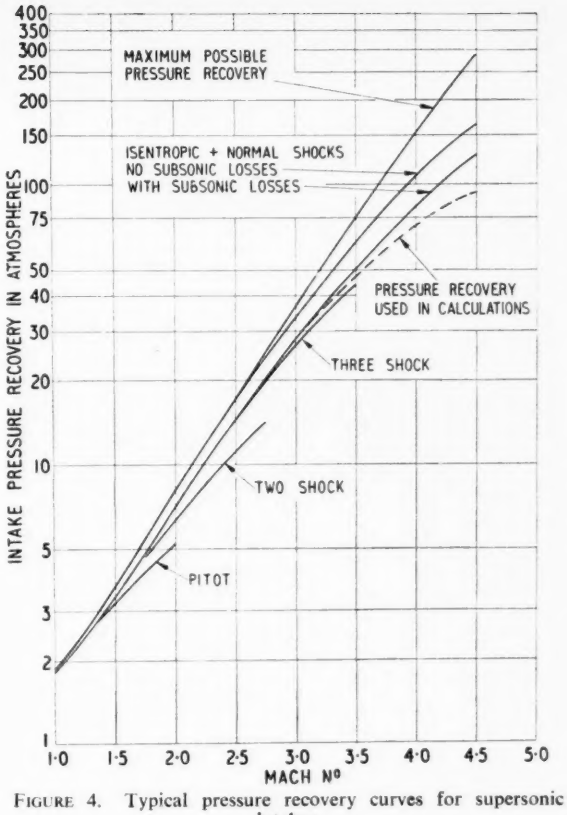



FIGURE 4. Typical pressure recovery curves for supersonic intakes.

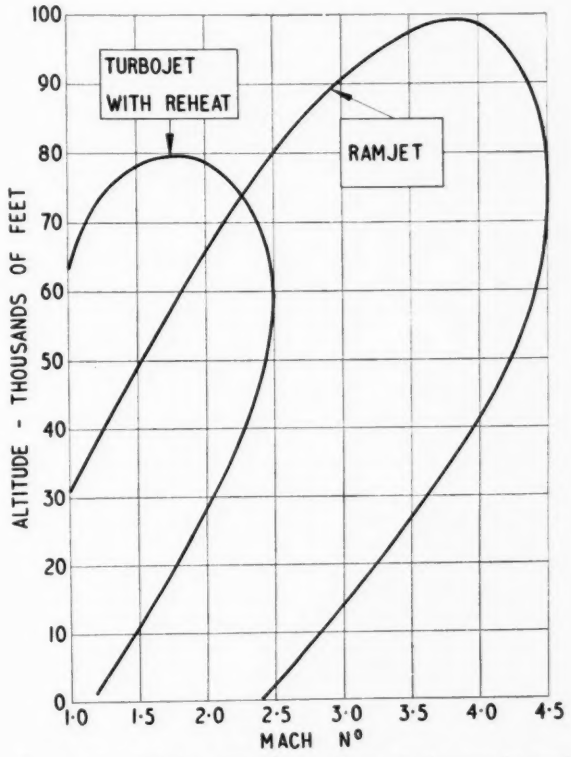



FIGURE 5. Relative operating regions of the ram-jet and reheated turbo-jet (*American source*).

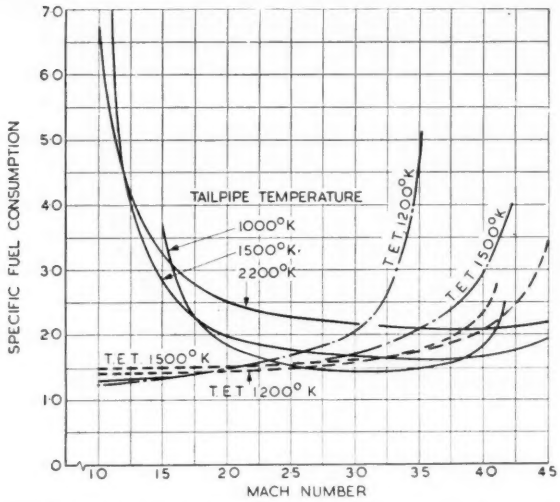



FIGURE 6. A comparison of specific fuel consumption obtainable from ram-jets and turbo-jets.

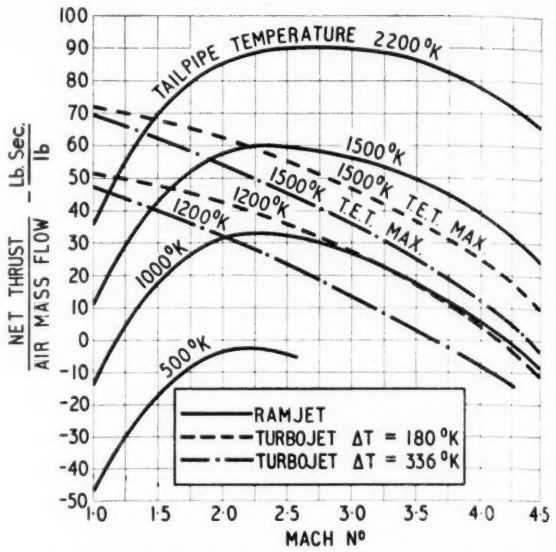



FIGURE 7. Comparison of net specific impulse from ram-jets and turbo-jets.

relative performance of selected ram-jet and turbo-jet engines. In Fig. 6 the specific consumption has been plotted against Mach number over a range from $M=1$ to $M=4{\cdot}5$ for ram-jet and turbo-jet engines. Ram-jet curves are for tailpipe temperatures of 1,000°K, 1,500°K, 2,200°K, and two kinds of turbo-jet engine have been considered. Firstly, a jet engine with a sea level static compression ratio of 5, with a compression temperature rise of 180°C., constant under all operating conditions. The second jet engine is one of a higher compression ratio of 10:1, sea level static, with a compression temperature rise of 336°C. Two turbine entry temperatures have been assumed for each engine—firstly 1,200°K representing current practice, and secondly, 1,500°K which is a temperature possibly attainable in the next few years. This figure shows how the specific consumptions of ram-jets are relatively extremely high in the range from $M=1$ to 2 but, as the Mach number rises above this value, consumptions become comparable with, and eventually better than, those obtained with turbo-jet engines. This is basically because, with the extra compression applied by the turbo-jet engines, optimum compression ratio for the temperature range has been passed. In other words, at these high Mach numbers, the compression achieved in the intake is high enough to make further compression redundant or harmful. (It has been assumed in calculating these curves that the optimum intake conditions are maintained at all Mach numbers for both ram-jet and turbo-jet engines in line with the values shown in Fig. 4.) This, then, gives the picture as far as fuel consumption is concerned with two kinds of engine.

In Fig. 7 the specific impulse, *i.e.* thrust per unit of air mass flow has been plotted again against Mach number for the same range. The thrust employed here is the net internal thrust of the whole engine and intake combination, and allows for intake drag. This diagram clearly shows the superiority of the power output of ram-jet engines for Mach numbers greater than 2. In particular, the very great advantage can be seen that the ram-jet has in its ability to use a high tailpipe temperature of 2,200°K., compared with the current practice of about 1,200°K. for a turbo-jet. At a Mach number of 3, for example, this gives a superiority of roughly 3:1 in favour of a high temperature ram-jet.

Figure 8 shows the same picture presented in the form of thrust coefficients, and here the effect of the intake pressure rise on the mass flow through ram-jet engines is clearly brought out. At the lower speeds, owing to the relatively small intake compression ratio, the mass flow per unit area and, therefore, the thrust per unit area, is relatively low, but above a Mach number of 2 this condition is reversed. These curves show the general picture for a cruise condition and reveal clearly how a ram-jet becomes thermodynamically competitive above, say, $M=2$. However, they do not present the whole picture as they do not allow for:—

(*i*) The relative simplicity and lightness of a ram-jet engine.

(*ii*) The relative low cost of a ram-jet engine.

(*iii*) The ability of the ram-jet to use a high maximum temperature.

(*iv*) The mechanical difficulties of operating turbo-jet engines at high ram temperatures, for example, in cooling of bearings and high temperature rotating parts.

(*v*) However, against these advantages, the ram-jet must be brought up to an operational speed to become effective and, therefore, requires to be used in conjunction with an acceleration engine.

This, then, shows that a ram-jet has a definite claim as a propulsion unit for high supersonic speed aircraft of all kinds, but many factors have to be taken into account before it can be decided whether ram-jets, turbo-jets, or a combination of the two would be employed for any given duty. However, the following general conclusions can be drawn:—

(*i*) The ram-jet is the obvious choice for a relatively short-range guided weapon at speeds down to $M = 1{\cdot}5$ where its lightness and low cost outweigh the high fuel consumption.

(*ii*) A ram-jet is obviously an excellent engine for the long-range guided weapon cruising at a Mach number above 2·5, where flexibility of operation is not called for.

(*iii*) A manned aircraft needs more flexibility and, although a ram-jet suits machines designed to fly above Mach numbers of 2·5 very well, it must be combined with another unit for take-off and low speed cruise. Analysis has shown that attractive combined power plants can be designed.

With the ability to cruise more economically at high Mach numbers on ram-jets alone, there is a good case for shutting down the accelerating turbo-jets in the difficult region, or, at any rate, running them under low load conditions. This would greatly ease the design problems for providing such engines.

(*iv*) The question of re-heat has not been brought in as it would complicate the picture and essentially amounts to the same thing as a turbo-jet plus ram-jet, except that the re-heat fuel would be burned less effectively than in a ram-jet. Where and when it would be employed would depend largely on the aircraft requirements.

## Intakes

Having looked at the general field of application for ram-jet engines, particularly relative to turbo-jets, consideration is now given to the separate components of a ram-jet engine beginning with the intake, as this not only comes first logically but it is the component which largely determines the character of the engine. First of all, consider the shock regimes of a single-cone intake. There are numbers of intakes to choose from, but the simple conical spike type has many advantages, among them that it suits ram-jet requirements approximately and lends itself to matching changes. This relatively simple intake design finds applications up to about $M = 3$. Above this figure the losses incurred in the two-shock system become excessive (*see* Fig. 4) and more

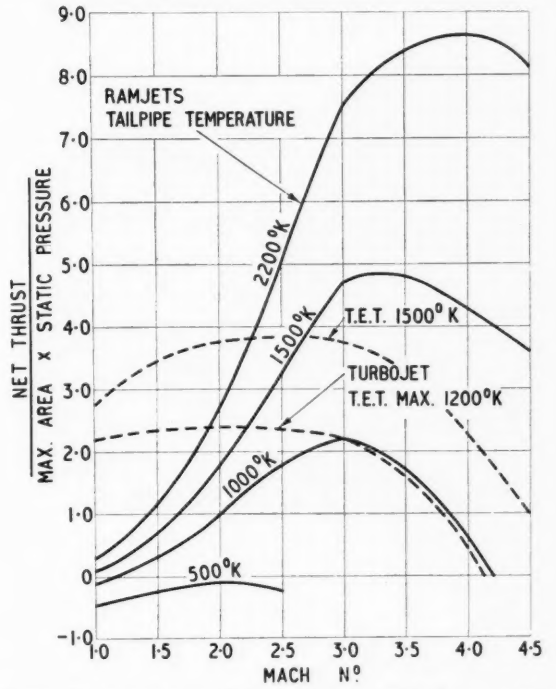
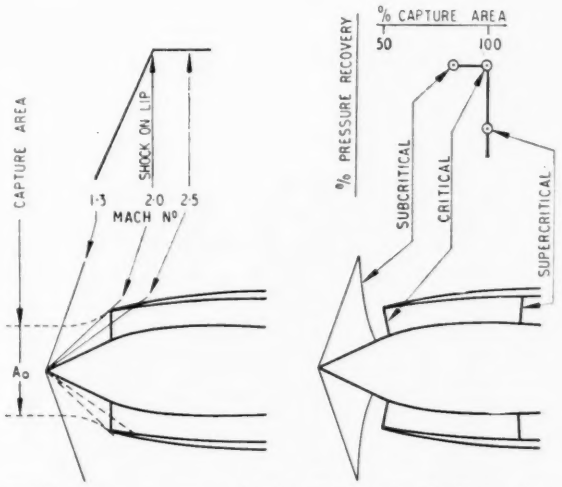



FIGURE 8. Comparison of net thrusts obtainable from ram-jets and turbo-jets.

elaborate designs are required. These can take the form of multiple cones, convergent divergent ducts, isentropic cone, or combinations of these features. These, of course, are all axi-symmetric, three-dimensional intakes which have two-dimensional equivalents. The general characteristics of all these types are similar, so that discussion will be confined to the single-cone intake. The shock patterns obtained under different operating conditions are shown in Fig. 9.




Significance of cone shock position. Significance of diffuser shock position.

FIGURE 9. Shock waves on a conical intake.

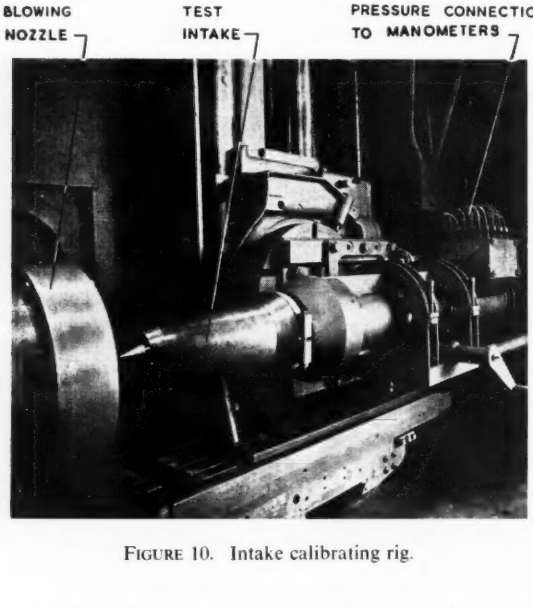



FIGURE 10. Intake calibrating rig.

The left-hand diagram of this figure shows the effect of varying the flight Mach number. As the Mach number rises, the cone shock angle becomes progressively more acute until eventually the shock touches the intake lip. At higher Mach numbers it is reflected inside the engine intake. This affects the "capture area" of the air flowing into the engine. This is defined as the area of the stream tube at infinity through which air entering the intake flows. Owing to the deflection of the stream lines through the conical shock, the capture area progressively increases with increasing Mach number until the shock touches the intake lip. The capture area is then equal to the area of the intake lip and thereafter remains constant with increasing speed. The graph above the left-hand diagram illustrates this point.

In the right-hand diagram the effect can be seen of varying the ram-jet temperature ratio at a constant flight Mach number. As mentioned earlier, a low temperature ratio brings a relatively high Mach number at the diffuser exit (*see* Fig. 2). To satisfy this condition the normal shock travels well into the intake so that there is supersonic flow within the intake between the lip and the normal shock and subsonic flow thereafter. As the temperature ratio is increased, the normal shock is pushed towards the intake lip. At the same time the pressure recovery is improving until, when the shock is actually in the intake lip, there is what is known as the critical condition, and this, in general, represents the condition of optimum pressure recovery. Further increase in the temperature ratio drives the normal shock out of the intake so that the air entering the intake lip is now flowing subsonically, and to satisfy flow continuity some of the air is spilt outside the intake lip. This is a subcritical condition. It is sometimes convenient to take advantage of this region in seeking an engine with a wide range of operation. Nonetheless, subcritical operation is, in general, an undesirable condition, as mass flow is being lost through the intake and, at the same time, the intake drag is being increased due to an increased pre-entry drag of the divergent subsonic stream line. Under some conditions, if the normal shock is expelled too far, *i.e.* if it moves too far into the subcritical region, the flow becomes unstable and the engine suffers from a condition of intake buzz, which is an oscillatory flow condition equivalent to compressor surge in a rotating engine. Operation in this region is usually too rough and inefficient to be tolerable.

Figure 10 shows the kind of free-jet wind tunnel which has been used for intake development, with an intake model in position. Figures 11 and 12 are schlieren pictures obtained in this wind tunnel with a typical intake model. These pictures were taken with

Schlieren photographs of shock waves on a typical ram-jet intake. $M = 1{\cdot}8$. Semi-cone angle $= 25°$.

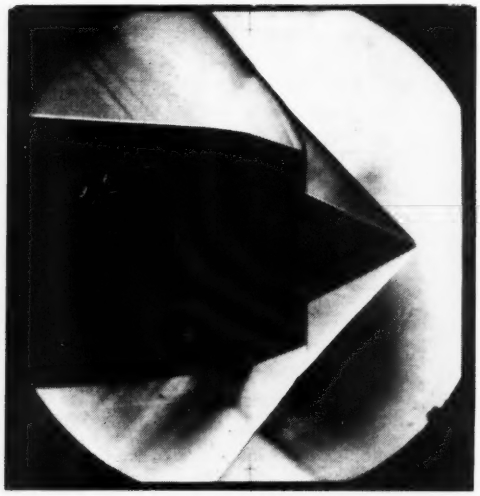


FIGURE 11. Supercritical operation.

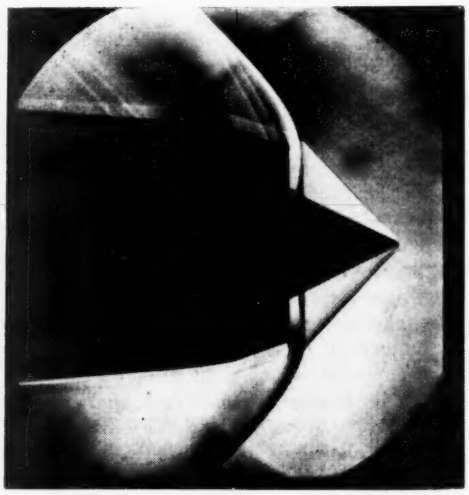


FIGURE 12. Subcritical operation.

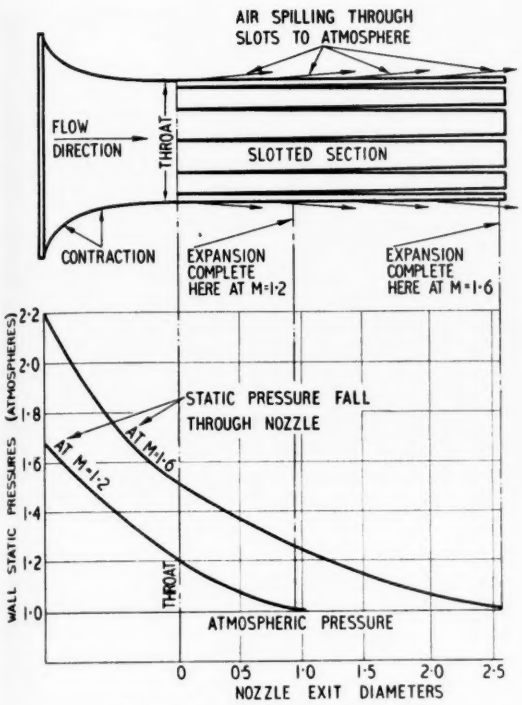
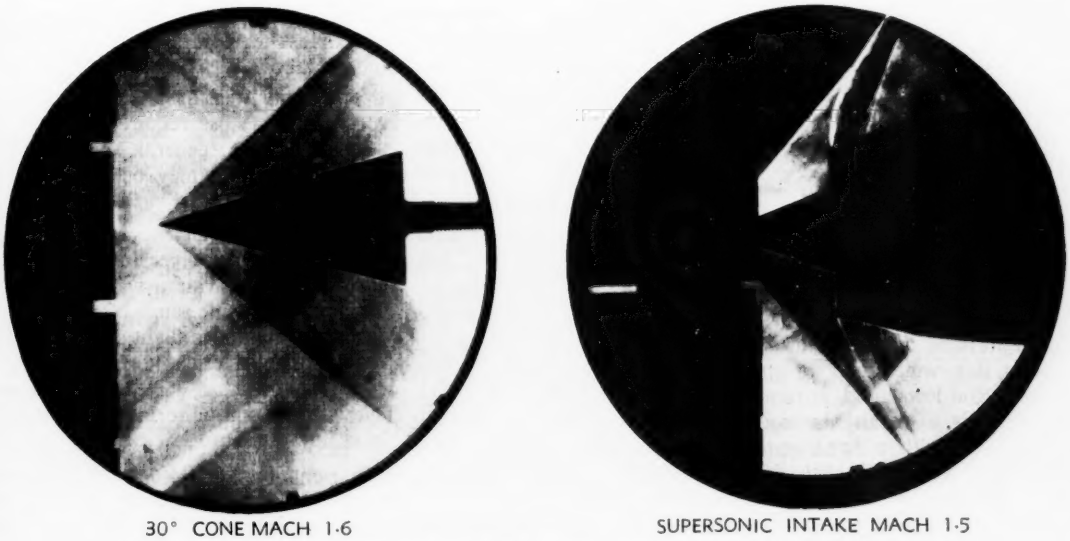



FIGURE 13. The slotted nozzle.

the intake operating at a Mach number of 1·8. Figure 11 shows supercritical and Fig. 12 subcritical operation.

In Fig. 13 is seen a diagram of a piece of equipment which has been developed during the course of this work and which has been found of the greatest use in ram-jet development—both in the intake wind tunnel and also in free-jet testing of ram-jet engines. This is a slotted nozzle which is a device which gives a variable Mach number nozzle of very simple construction. Its principle is illustrated in Fig. 13 and it has been found possible to produce a jet with a Mach number uniform with $\pm 2$ per cent over a range from low subsonic to about $M = 1{\cdot}6$. It is only necessary to vary the applied blowing pressure to attain the required Mach number. Figure 14 shows Schlieren pictures taken in the intake tunnel using this form of nozzle. The straightness of the conical shock gives an indication of the uniformity of the flow field.

Next consider the characteristics of a typical ram-jet intake. These are presented in Fig. 15 for an intake of the single-cone, two-shock type designed for operation at a Mach number of 3. The ordinates of this diagram give the relative diffuser exit pressure plotted against the relative non-dimensional mass flow function $W\sqrt{T}/P$, with a value of unity at the design point. The curves extending from the critical line to the right of the diagram represent supercritical operation and under these conditions at any Mach number the mass flow is constant. These curves of constant mass flow take this hyperbolic form because they are plotted against diffuser *exit* pressure. To the left of the critical line the curves bend into the normal horizontal direction in the subcritical region. Here the mass flow function is falling due to subsonic spill. This region is bounded by the limit of subcritical flow stability; if the mass flow is diminished to bring operation into this unstable zone buzz conditions result. These are the intake characteristics. Plotted on the same diagram are ram-jet working lines for three restrictor sizes, 60, 70 and 80 per cent relative area, restrictor throat to tailpipe. All these lines are plotted for an intake operating at an effective fuel/air ratio of 0·05 in the stratosphere. Looking at the 70 per cent restrictor line, it is seen that this would give critical operation at a Mach number of 2·5 and this would represent the optimum operating point for this



30° CONE MACH 1·6 SUPERSONIC INTAKE MACH 1·5

FIGURE 14. Schlieren photographs using slotted nozzle. The straightness of the conical shocks indicates a uniform nozzle exit velocity distribution.

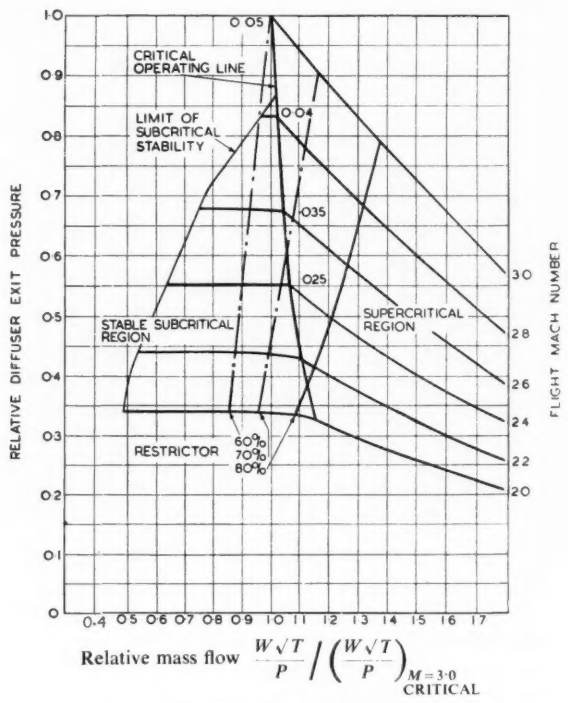



FIGURE 15. Typical intake characteristics.

size of restrictor and fuel/air ratio. With further increase in Mach number the temperature ratio would fall owing to the rising ram temperature and operation thereafter would be supercritical, so that at a Mach number of 3, a relative pressure recovery of 0·9 is attained. As this working condition is decided only by the temperature ratio and the relative restrictor area, there is the interesting result that an improvement in the maximum potential intake recovery would not give any benefit in engine operation. A working curve for an engine with a 60 per cent restrictor, would be operating at optimum conditions at the design point of $M=3$ and 0·05 fuel/air ratio. This would be an engine optimised to cruise at these conditions. In this particular intake there is an unstable subcritical region until the Mach number falls to about 2·85 so that the reduction in speed of this engine would require a reduction in the applied fuel/air ratio to maintain stable operation. Figures placed against the critical line show the fuel/air ratios which would be needed to keep the 60 per cent engine operating critically at the lower Mach numbers.

The right-hand curve for the 80 per cent restrictor shows that if a wide range of speed, with high performance at the lower end, is required from a ram-jet engine, there is a penalty in top speed performance when operating with a fixed geometry intake. This gives a general illustration of the influence of the intake design on the ram-jet behaviour, and it is evident that there is scope for assisting engine matching by variable geometry. This can take a number of forms, all of which seriously complicate the engine mechanically, but some to a greater extent than others. Things that can be done are:—

(*i*) Vary the engine annulus area.
(*ii*) Vary the cone shock-on-lip Mach number. (This has the effect of controlling the capture area at a given flight speed).
(*iii*) By-pass air from the intake back into the free stream.
(*iv*) Vary the area in the final nozzle.

All of these, obviously, will need close scrutiny before they are adopted. Which particular form of variable geometry is adopted will depend on the nature of the matching problem. For instance, by-passing air from the intake is wasteful as the air would have lost momentum passing through the intake, but being simple it is probably a desirable method to adopt in the case of a supersonic turbo-jet, in which, in addition to varying the speed of the engine relative to the air, the rotational speed of the engine can also be varied and, hence, its swallowing capacity greatly affected.

In the discussion so far the intake properties which have been mostly stressed have been pressure recovery and matching to the engine requirements. However, in developing a successful intake other operating conditions would have to be taken into account under which the intake effectiveness must be maintained. In particular, it is desirable that it should tolerate angles of attack without serious loss of performance. In addition, a ram-jet engine requires a reasonably uniform velocity profile at entry into the combustion chamber and steady flow conditions.

## Combustion

After the air is compressed, it must be heated. This is done by mixing fuel with the air and burning it as completely as possible. The process is much like reheat, but at present flight speeds starts from a lower initial temperature, although temperatures comparable with turbine exhaust temperatures would be obtained at Mach numbers above $3\frac{1}{2}$.

The properties required of a ram-jet combustion chamber are typical of those required from jet engine combustion chambers in general, except that the emphasis on some of them may be slightly changed. These may be listed as:—

(*i*) High combustion efficiency.
(*ii*) A wide range of temperatures (wide fuel/air ratio limits to provide a wide thrust control).
(*iii*) Tolerance of a wide range of pressures resulting from variation in flight speed and altitude.
(*iv*) A wide range of Mach numbers.
(*v*) Low pressure loss.
(*vi*) Tolerance of non-uniform velocity profiles.
(*vii*) Good flow stability.

In a short ram-jet engine combustion is sensitive to the velocity profiles resulting from shock waves and boundary layer patterns and for this reason we have to test in the free-jet condition to ensure that the engine will operate correctly in flight.

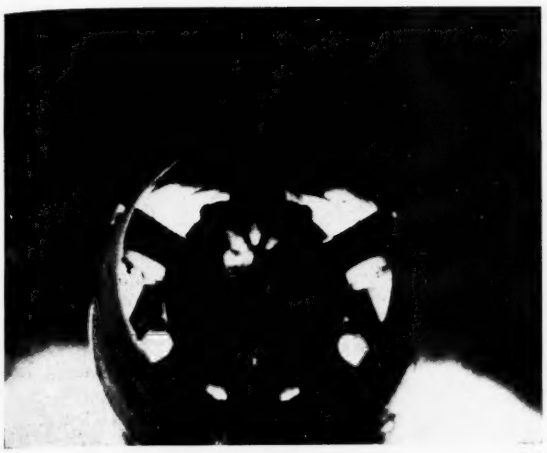


FIGURE 16. View looking into a ram-jet intake showing asymmetric flow on nose cone during the boost phase.

Free-jet testing ensures that the duct system is fully representative of the flight engine where risks of flow pulsation and resonance are involved. In addition to ensuring effective operation under steady conditions, it is important to get the combustion chamber alight. In a missile engine this is a particularly difficult problem, as the engine has to be lit and delivering full thrust within about two seconds from launch, after a prolonged period of storage. This means that the fuel must be delivered and correctly metered in this phase and a "sure-fire" system of flame ignition applied. We have used pyrotechnic flares for ignition with magnesium for fuel and strontium nitrate as the oxidant. This oxidant was chosen primarily for its storage properties, but it has proved extremely useful in flame photography owing to the high red luminosity it imparts to the ram-jet flame.

The light-up problem has two main aspects—firstly to handle combustion as such through the transonic regime where the air is relatively cool and its flow through the intake is to a large extent indeterminate; and secondly, to ensure that the fuel system is metering correctly during the high launch accelerations and rapidly changing conditions. An illustration of part of this problem is given in Fig. 16 which shows a photograph taken of a ram-jet intake during launch conditions. The white streaks from the nose cone are fuel spilling through small holes in the cone, and show that the flow through the intake is far from symmetrical. This condition arose from shock-wave boundary layer inter-action during the launch phase. As the Mach number increased, the offending shock-wave moved aft past the engine intake and the flow became symmetrical. This sort of disturbance must be tolerated by the ram-jet during light-up conditions, so combustion has had to be tested during steady transonic conditions and also, in conjunction with the flight fuel system, under the transient transonic conditions encountered during launch. Experience has shown that it is relatively easy to match a ram-jet to operate under any single specified condition. The art of the game comes in securing effective operation over the full range of altitude and forward speed under both steady and rapidly changing conditions. Getting an operational ram-jet has been a process of tuning the whole system to give performance stability and reliability over this wide range.

One of the properties required of the combustion chamber is "combustion range" where this implies the ability to burn over a wide range of mixture strengths to give good thrust control in flight. Figure 17 shows a typical ram-jet engine "power curve" where the net internal thrust has been plotted as a function of the equivalence ratio. This shows that maximum power occurs as in a motor car engine, slightly on the rich side of correct mixture, and that as the engine is weakening off the thrust falls and, in fact, is still under control at negative values, so that thrust is controlled from +100 per cent to approximately −60 per cent of the rated thrust. The negative thrust region, of course, comes when the intake drag is dominant at weak mixtures. Flow stability (*i.e.* freedom from velocity fluctuations) has already been cited as an essential property of a ram-jet combustion chamber.

The flow instabilities encountered have been of two main kinds. One is called pulsing and this takes the form of a longitudinal oscillation of the column of air and burning gases within the ram-jet which is tuned to the organ pipe frequency of the engine. This can attain a high amplitude and be very destructive. Pressure fluctuations with amplitudes approaching ±100 per cent of the steady operating pressure have been measured at frequencies in the range of 25 to 100

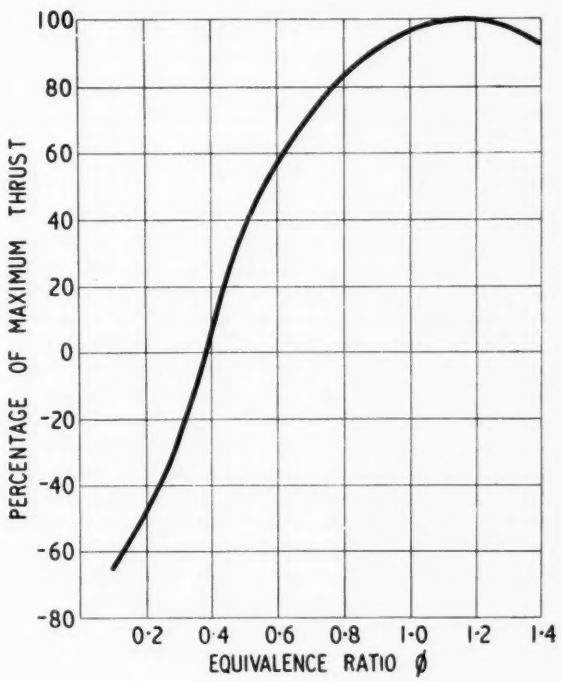



FIGURE 17. Ram-jet thrust-fuel flow.

cycles per second. When it is realised that engine thrust can also vary through a range of about ±100 per cent under these conditions, the risk to the aircraft structure can be seen to be large. Pulsing flow of this nature was encountered in early flights of our engines, but was corrected by alterations to fuel injection arrangements. The destructive effect produced by these pulsations is well illustrated in Fig. 18 which shows how an intake nose cone has been crushed in a pulsing ram-jet during sea-level rig testing.

The second form of combustion instability encountered has been screech. This phenomenon has also caused considerable trouble in turbo-jet re-heat installations and has been identified as an oscillation of the combustion gases in a generally tranverse (as opposed to longitudinal) mode, at considerably higher frequencies than those found in pulsing vibration. Frequencies are of the order of 1-2 K cycles and a well-developed screech condition can cause destruction of the components of the engine within a very short time. Fatigue failures of flameholders and engine cases can occur within seconds and have the general appearance of fractures in broken glass. At first, on our engines, screech was ignored—or rather regarded as beneficial—as it seemed to be accompanied by improved combustion efficiency. However, it became much intensified as a wider range combustor was developed, and although matters were kept under control for a time by strengthening the engine components, in the end, screech had to be dealt with in its own right because the vibration emanating from it upset the engine fuel controls and would have been a serious problem to the electronic engineers. Effective cures have been applied to deal with this problem, and in this connection I should like to acknowledge the great assistance we have had through the Gas Turbine Collaboration Committee from the excellent work on screech of Mr. S. L. Bragg of Rolls-Royce Ltd.

## Fuel System

The general requirements of a fuel system for ram-jets are very similar to those which have become familiar in other air-breathing engines. In other words, tanks and a pumping system are required, fuel metering components and controls for operating the engine. Because hydrocarbon fuels are used no specifically novel techniques are involved from the chemical aspect, but the fuel tanks must be capable of dealing not merely with negative "$g$", but "$g$" in all directions. This is really characteristic of a supersonic aeroplane and arises from the fact that with such aircraft, thrust and drag can exceed the weight of the aircraft and, particularly in missile applications, manoeuvre accelerations can also be very high. This is one reason why a human pilot is an embarrassment in seeking maximum military performance. Others are that he sees indifferently and thinks too slowly. Nonetheless, the human pilot has great versatility and among his many duties in an aircraft he has virtually formed part of the fuel control system.

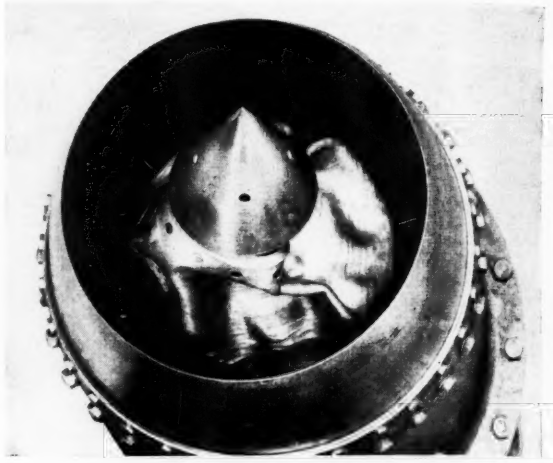


FIGURE 18. Photograph of a rig engine intake showing the damage caused by pulsing combustion.

With regard to fuel pumps, the problem is similar to that encountered in turbo-jets. A ram air turbine has been used to drive the centrifugal fuel pump. This has been a most effective and reliable unit. There have been special problems due to the increasing range of pressures and fuel flows resulting from flight to higher and higher altitudes.

The specific requirements for fuel controls for a ram-jet engine are:—

(*a*) To control the mixture strength for maximum thrust, (*i.e.* to act as a carburettor). Compensating for speed and altitude.
(*b*) To provide thrust control.
(*c*) To keep the fuel supply within the combustion range.
(*d*) To provide the correct fuel flow during launch transients.

Neat, compact units to perform these functions have been developed by Messrs. Joseph Lucas and by Messrs. H. M. Hobson in collaboration with the Bristol Company. The acceleration conditions mentioned in connection with tanks apply also to the fuel controls, and it is necessary to ensure that the accuracy of the fuel controls is kept within acceptable limits during high accelerations. For these reasons care is taken to mount the controls so that the moving components are placed favourably with regard to the worst acceleration forces, and part of the development testing involves measuring their behaviour under "$g$" conditions on centrifuges. Similar precautions are taken to ensure that engine and airframe vibrations do not impair the accuracy of the controls.

It is characteristic of missiles that they may be kept for long periods under storage conditions and then have suddenly to be put into flight without preliminary run-up checks, such as are customary in manned aircraft. This has raised special problems associated with possible dirt in the fuel system. From experience, we have arrived at a philosophy where it is assumed that

the fuel is likely to be dirty and the fuel system components have been designed and developed to operate with dirty fuel. So many organisations are involved in assembling the various components of a missile that it becomes extremely difficult to ensure that dirt does not enter at any point. Accordingly, it has become standard development procedure to test all components with fuel containing "British Standard Dirt" in recommended proportions. We found by experience, however, that even after this procedure, failures were occurring due to fuel contamination—particularly from fine particles of swarf. Accordingly, the procedure was modified to include a proportion of dirt obtained from the Assembly Shop floor. This was found to be more detrimental than "British Standard Dirt," and when designs had been altered to cope with it, reliability was much improved.

## Testing

In previous sections a ram-jet has been defined, its place in the air-breathing supersonic propulsion field has been considered and some of the problems in its component sectors have been discussed. Now there is another phase of the problem to bring this kind of engine to a practical, reliable reality. That is testing and test techniques. This is a most important subject for we are now entering an era of supersonic propulsion by air-breathing engines in which the problems of designing, building and operating the test equipment rank alongside those posed by the engines themselves.

There are four factors involved:—

(*i*) A large or dominant part of the air compression takes place in the intake, so supersonic flow fields are necessary to test performance and controls.

(*ii*) High ram temperatures impose special structural problems.

(*iii*) High ram pressures are possible and impose special stresses and vibration problems on air loaded components.

(*iv*) High altitudes impose low pressures and as there are, militarily and economically, prizes to be won by getting as high as possible, these conditions have to be studied as well. Combustion and controls are especially sensitive to the adverse effect of low pressures.

Finally, there is no complete substitute for flight-testing, and this is especially true of ram-jets. In our case we have had to do the job in expendable missiles and this has brought its own techniques and philosophies. Accordingly, some of the equipment and techniques will be described which have been evolved for the development of our ram-jet engines.

The intake wind tunnels have already been mentioned, while the fuel system components are not so different from those of turbo-jets as to demand especially novel methods. So my main remarks on ground-testing will be confined to ram-jet engine and combustion testing.

The first important factor, which is self-evident, is that a ram-jet will not run itself and needs a great deal of compressed air. This we have in the Compressor and Turbine Test House with 26,000 h.p. installed. This has served us well, but, of course, it is not nearly enough!

We test "connected" or "free-jet." In connected testing, the combustion chamber on a ram-jet is connected directly to the air supply. This economises in air but does not simulate the true behaviour of the engine in the supersonic stream. To meet this condition, free-jet testing is applied. Figure 19 shows a ram-jet engine set-up for this form of test. It will be noted that the supersonic nozzle diameter is only slightly greater than the diameter of the intake lip, because compressed air supply is limited and expensive and we cannot

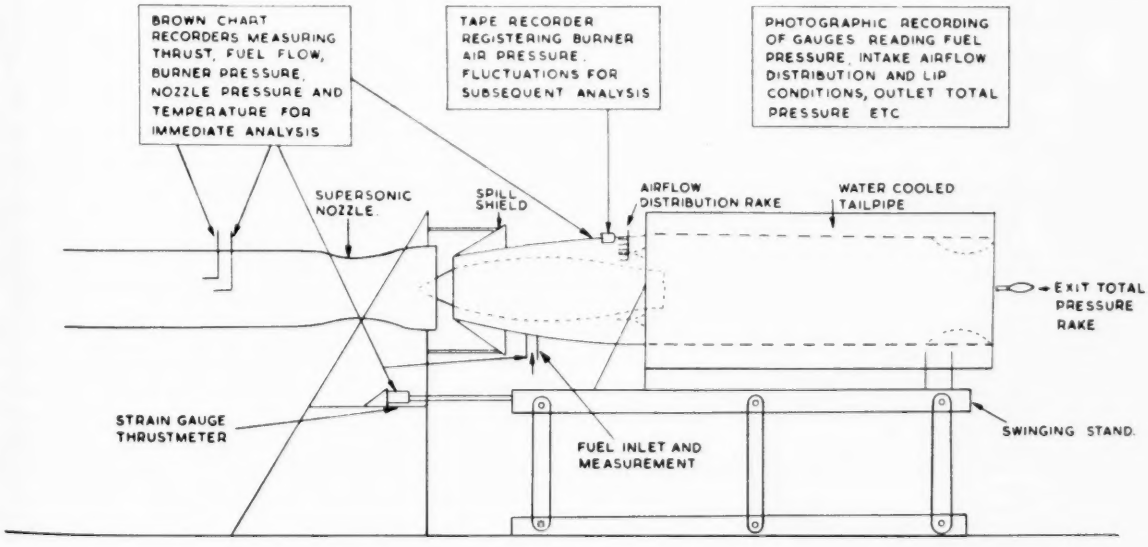

BROWN CHART RECORDERS MEASURING THRUST, FUEL FLOW, BURNER PRESSURE, NOZZLE PRESSURE AND TEMPERATURE FOR IMMEDIATE ANALYSIS
TAPE RECORDER REGISTERING BURNER AIR PRESSURE FLUCTUATIONS FOR SUBSEQUENT ANALYSIS
PHOTOGRAPHIC RECORDING OF GAUGES READING FUEL PRESSURE, INTAKE AIRFLOW DISTRIBUTION AND LIP CONDITIONS, OUTLET TOTAL PRESSURE ETC
SUPERSONIC NOZZLE
SPILL SHIELD
AIRFLOW DISTRIBUTION RAKE
WATER COOLED TAILPIPE
EXIT TOTAL PRESSURE RAKE
STRAIN GAUGE THRUSTMETER
FUEL INLET AND MEASUREMENT
SWINGING STAND

FIGURE 19. Free-jet testing.

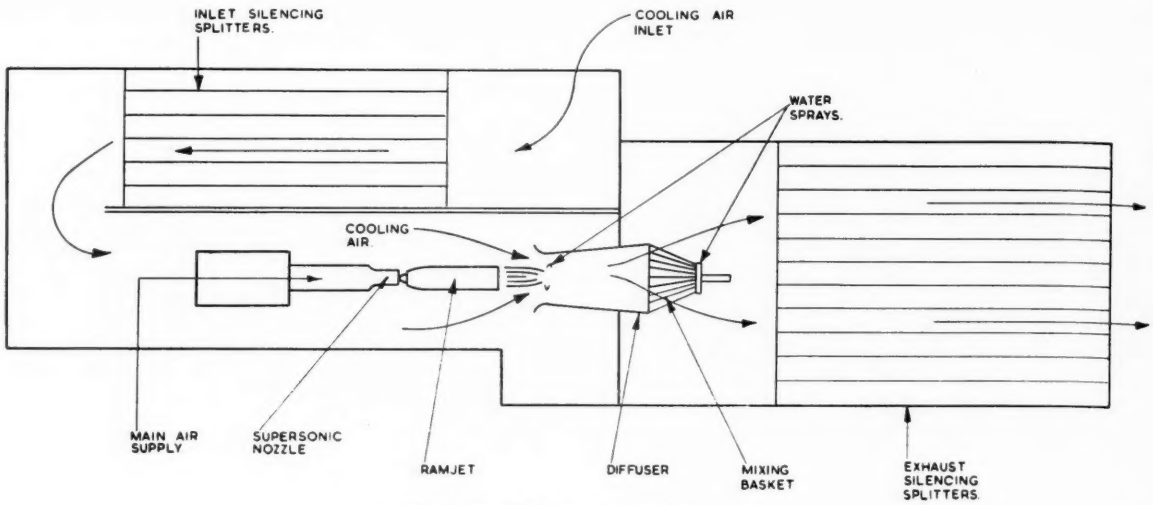



FIGURE 20. Buildings for ram-jet test rig.

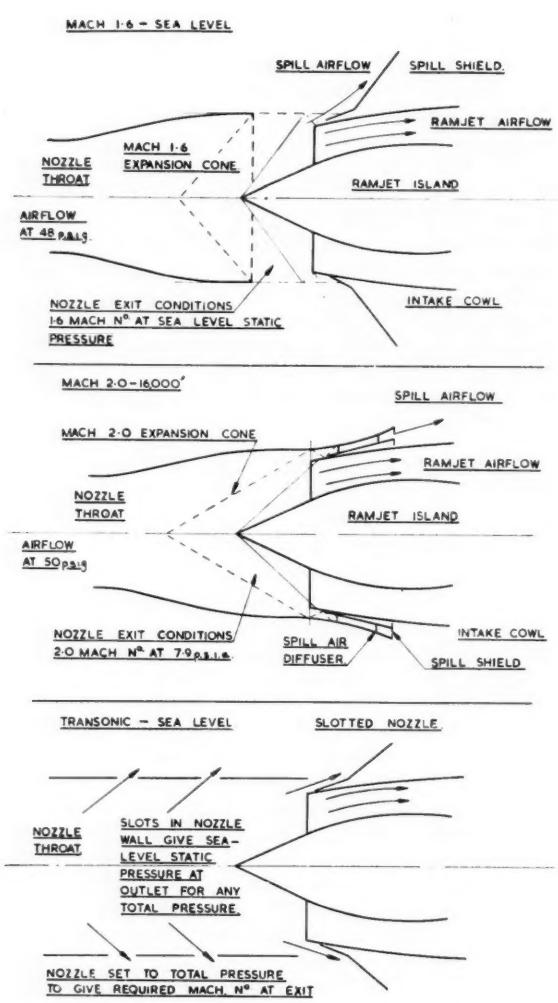

MACH 1·6 – SEA LEVEL
SPILL AIRFLOW
SPILL SHIELD.
RAMJET AIRFLOW
NOZZLE THROAT
MACH 1·6 EXPANSION CONE.
RAMJET ISLAND
AIRFLOW AT 48 p.s.i.g.
INTAKE COWL
NOZZLE EXIT CONDITIONS 1·6 MACH N° AT SEA LEVEL STATIC PRESSURE
MACH 2·0–16,000'
SPILL AIRFLOW
MACH 2·0 EXPANSION CONE
RAMJET AIRFLOW
NOZZLE THROAT
RAMJET ISLAND
AIRFLOW AT 50 p.s.i.g.
INTAKE COWL
NOZZLE EXIT CONDITIONS 2·0 MACH N° AT 7·9 p.s.i.a.
SPILL AIR DIFFUSER
SPILL SHIELD
TRANSONIC – SEA LEVEL
SLOTTED NOZZLE
NOZZLE THROAT
SLOTS IN NOZZLE WALL GIVE SEA-LEVEL STATIC PRESSURE AT OUTLET FOR ANY TOTAL PRESSURE.
NOZZLE SET TO TOTAL PRESSURE TO GIVE REQUIRED MACH. N° AT EXIT

FIGURE 21. Nozzle-intake assemblies for free-jet testing.

afford a great deal of spill. It is important to ensure that reflections of the cone shock-wave on the jet boundary do not interfere with flow into the engine.

When about 20,000 air h.p. is being applied, with fuel flow to match, the process of testing a ram-jet engine is hot and noisy and as the test beds—as appears to be customary in the Aero-Engine Industry—are situated fairly close to residential areas, a great deal of effort has been expended on test-bed silencing. Figure 20 shows a typical sea-level test house.

Figure 21 shows some set-ups on free-jet testing. The top diagram shows the arrangement when the supersonic nozzle is fully expanded to the test-bed static pressure and it will be seen how the shock reflection is deflected to the outside of the intake cowl. The spill shield is fitted to collect the spill air from the free-jet and deflect it away from the engine cowl so that true internal thrust measurements can be made. The centre diagram shows the test arrangement required when testing at a Mach number of 2. In this case, with the blowing pressure available at 50 p.s.i. gauge, the supersonic nozzle would not be fully expanded at the test-bed static pressure and it is necessary to diffuse the spill air. This is done by mounting the engine in the manner shown, using a spill air diffuser. The effect of this is to increase the pressure altitude at which the test takes place, in this case to 16,000 ft. It is important when using this technique to ensure that there is enough pressure to keep the ram-jet propelling nozzle choked. The lowest diagram shows the set-up for testing in transonic conditions at sea-level, using a slotted supersonic nozzle. With this set-up simulated launch tests can be done with the full missile fuel system. Automatic valving to the air supply is provided, by which the rise of Mach number with time which occurs in a rocket-boosted launch can be accurately simulated, and the engine can be started from cold static conditions and brought up to full power at a Mach number of 1·5 within about 2 seconds.

Figure 22 shows a ram-jet on a test-bed with

a slotted nozzle in position. The engine shown has internal components typical of a flight design, but is fitted with an extra heavy casing and a water-cooled tailpipe to allow for repeated testing on ground rigs. A great deal of work can be done on such a sea-level rig, but it is also necessary to do tests under low pressures simulating altitude. Low pressure is induced by using air ejectors.

Arrangements for altitude testing a ram-jet engine are shown in Fig. 23 in which compressed air is used to drive ejectors for exhausting the ram-jet engine which has to be tested "connected" because there is insufficient capacity to provide free-jet tests under all altitude conditions at the present time. However, it is an urgent requirement to improve our test capacity and, in particular, to allow free-jet testing at all altitudes, so that the whole engine and its control system can be handled under realistic flight conditions. Figure 24 is a photograph of a model of the new Altitude Test Plant which is now being installed for this purpose. The engine will be mounted in a steel drum which will be exhausted to low pressure by means of steam ejectors, thus releasing the whole of the air supply for application to the supersonic nozzle. Steam has been chosen as the exhausting agent because it lends itself to energy storage in accumulators and provides a satisfactory system at a relatively low cost compared with turbo exhausters. As the tests can be of short duration, and in view of the very high cost of running a plant of this nature, automatic recording is used for all test readings, as indicated in Figs. 21 and 23.

## Flight Testing

All our work on ram-jet flight-testing has been carried out on missiles flown at the Ministry of Supply ranges in Britain, and at the Weapons Research Establishment at Woomera, Australia, and this has had quite a strong influence on the techniques which we have evolved. We do as much as we can on ground-test, but flight-testing is absolutely essential, as we cannot fully simulate all ambient conditions, accelerations,

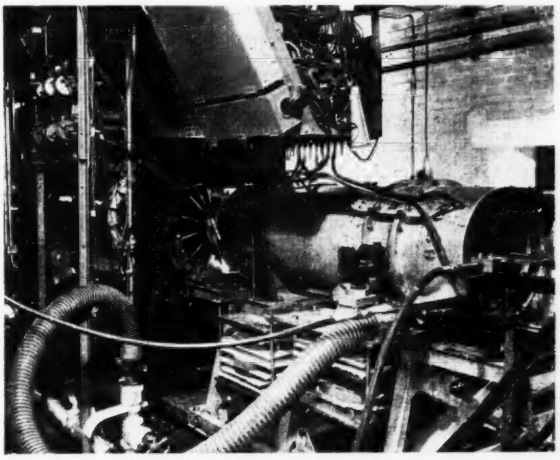


FIGURE 22. A heavy-gauge ram-jet engine on sea-level test bed, set up for launch testing.

*Note*: Water-cooled tailpipe, spill shield and slotted variable Mach number supersonic nozzle.

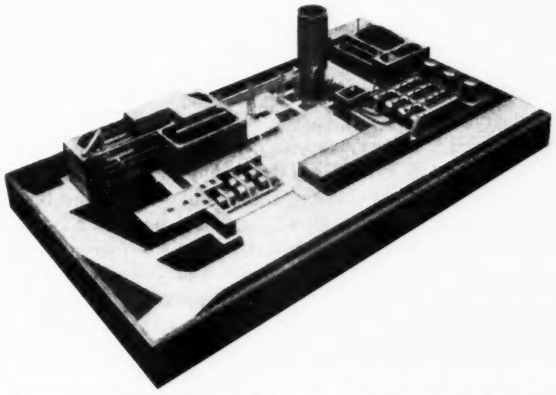


FIGURE 24. A model of the new ram-jet test plant under construction at Filton.

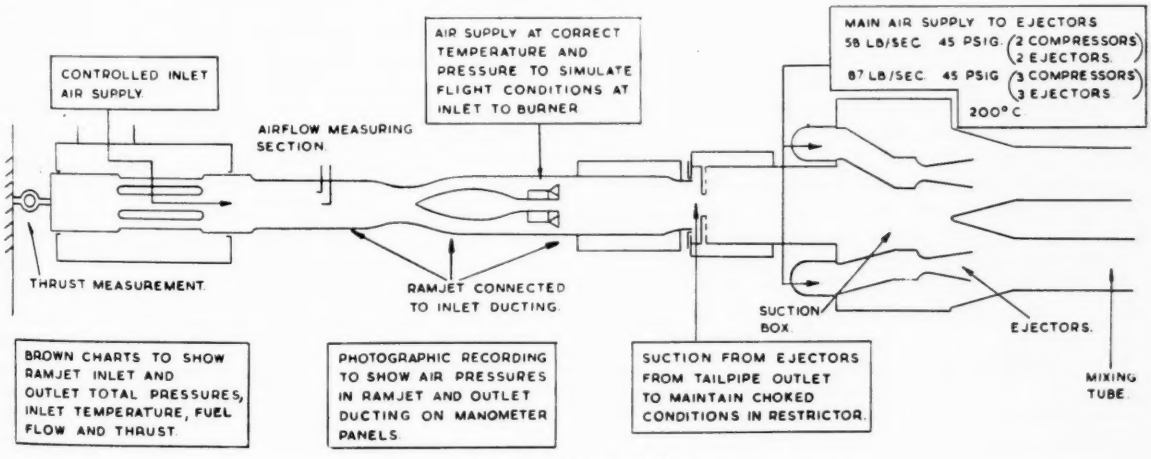

CONTROLLED INLET AIR SUPPLY.
AIR SUPPLY AT CORRECT TEMPERATURE AND PRESSURE TO SIMULATE FLIGHT CONDITIONS AT INLET TO BURNER.
MAIN AIR SUPPLY TO EJECTORS
58 LB/SEC. 45 PSIG. (2 COMPRESSORS, 2 EJECTORS.)
87 LB/SEC. 45 PSIG (3 COMPRESSORS, 3 EJECTORS.)
200° C.
AIRFLOW MEASURING SECTION.
THRUST MEASUREMENT.
RAMJET CONNECTED TO INLET DUCTING.
SUCTION BOX.
EJECTORS.
MIXING TUBE.
BROWN CHARTS TO SHOW RAMJET INLET AND OUTLET TOTAL PRESSURES, INLET TEMPERATURE, FUEL FLOW AND THRUST.
PHOTOGRAPHIC RECORDING TO SHOW AIR PRESSURES IN RAMJET AND OUTLET DUCTING ON MANOMETER PANELS.
SUCTION FROM EJECTORS FROM TAILPIPE OUTLET TO MAINTAIN CHOKED CONDITIONS IN RESTRICTOR.

FIGURE 23. Altitude testing.

vibrations and engine airframe interactions. All missiles are regarded as expendable, although those fired in Australia are recoverable in damaged condition, but others fired in Britain are lost in Cardigan Bay. This introduces a new factor into engine development compared with normal bench-testing. This can be summarised as "one test, one engine," whatever the result. To give an idea of what this means, imagine carrying out turbo-jet development under conditions where, after pressing the starting button, the engine is thrown away without examination, whatever the result, whether it started or not, or failed or not. We are also faced, as already mentioned, with the problem that an engine cannot be run up on the ground before it flies, so that when the button is pressed it must work and, this means that the instrumentation must work as well, for the process of flying expendable missiles and engines is obviously an expensive one. The instrumentation is quite elaborate and can be divided into two major types: airborne and ground instrumentation.

Airborne measurements are provided by telemetry sets which provide in-flight measurements of pressure, temperature, fuel flows, vibration, accelerations, mechanical displacements, and so on. Ground instrumentation provides measurements of speed, flight path and ambient conditions, and also provides high-speed film records of missile flight, especially valuable during the ram-jet light-up phase.

Large numbers of missiles are flown which are not subsequently recovered, but when operating on a land range, such as Woomera, it is possible to recover the vehicle after flight. When the useful part of the flight is completed, an explosive charge is fired which breaks the missile into aerodynamically unstable pieces which tumble to earth at a relatively low velocity. These components can then be picked up for examination. Although the impact speeds may be as high as 300 ft. per second, we have found that the components are not seriously damaged from the point of view of examination and, in fact, it has been possible to re-use some of the components. However, in cases where the self-destruction charge has failed and the missile has flown into the ground at supersonic velocity, damage is extremely severe and a ram-jet normally 9 ft. long has been picked up shortened concertina-wise to a length of less than 18 in. The recovered vehicles provide additional in-flight results from recorders, temperature paints and air-borne cameras, and it is difficult to over-emphasise the importance of getting such recovery. Mechanical failures have been found on some occasions but it has been equally important to ascertain when components have *not* failed, for malfunctions in flight revealed by instrumentation have, in some cases, been wrongly blamed on possible mechanical failures. Certain knowledge like this can save many abortive flight-tests.

Figure 25 is a photograph of a ram-jet recovered after flight. Stripes on the tailpipe are temperature-sensitive paints from which an accurate plot of the temperature distribution in flight is obtained. In this case, over-heating of the tailpipe had occurred in the region of the mounting fairing, and pick-up of light alloy on the tailpipe can be seen. This was rectified in subsequent designs. This ram-jet is quite heavily damaged, in fact, more so than is common on recovery.

FIGURE 25. A ram-jet recovered after flight in Australia.

To allow this kind of development in flight units, a paradoxical system has had to be evolved of having a line production of experimental units. Broadly the main airframe and engine structures can be pictured as being delivered on a moving belt from the Shops to the Test Range, and the experimental features have to be conceived, developed and applied in synchronisation with this moving line. Figure 26 is an attempt to show this process diagrammatically. The two lines of basic engines and basic missiles are shown proceeding through functional checks to the flight-test. In order to get adequate supplies of engines for expendable testing, we have to specify such basic standards so that the main components can be put into manufacture. Then, as development proceeds, specialised features are conceived and developed for application to the engine at the right part of the process. This calls for quite a nice estimation of the time by which specialsed features can be developed for inclusion in the missile instructions, as the process gathers so much momentum that it is a serious matter to upset the timetable..

New components for flight-test are shown coming in in from the left. Individual components, for example fuel controls are developed, fitted to rig engines and subjected to flight approval tests, which must be satisfactorily completed before they can be accepted for missile test.

The next stage is to carry out tests on the ground in flight engines (*i.e.* engines made to flight scantlings). While these tests are going on, the engines actually to be flown must have been instructed for manufacture, and these units are released for flight at the successful conclusion of the flight approval tests. All the components which go for flight-test are subjected to performance calibration and functional acceptance test before the engine is built. After assembly into the missile, final checks are made of the engine fuel system and the missile instruments. The whole missile is then transported to the range for flight-test. The diagram then shows the feed-back of flight-test data to complete the cycle.

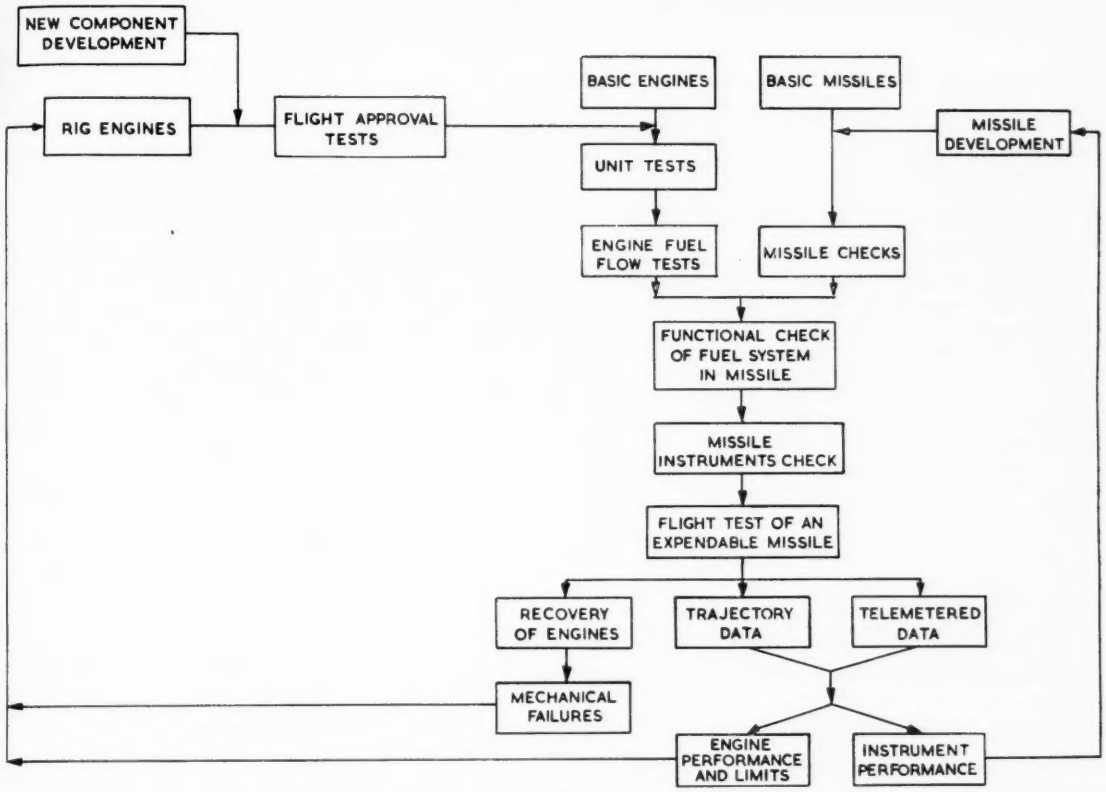



FIGURE 26. Ram-jet development by flight trials.

## Reliability

In thinking of the reliability of a ram-jet engine, when applied to a missile, one might feel that the problem is much eased by the relatively short flight-life required. From some points of view this is true but high reliability of a different sort is still essential in the form of sure start from storage, without check run-ups. It is easy to see that in an expendable aircraft containing a large number of components a very high degree of reliability is required from each of these components if a flight is not to prove abortive should any one of them fail. A very high degree of reliability has been achieved by meticulous acceptance-testing of components and sub-assemblies. As a result of this we can rely on these engines, after months of storage, being alight and delivering full thrust at more than 1,000 m.p.h. within two seconds of launching.

This process has been clearly shown in a colour film taken by cameras mounted in the bodies of missiles tested in Australia. Films such as these have been extremely valuable in assisting engine development. The records have provided information on the combustion processes and also on air flow behaviour (as shown in Fig. 16). The records have been invaluable as well, in monitoring possible mechanical failures during flight. There has been, at times, a good deal of heart-break in developing ram-jet engines and also quite a lot of fun; seeing this film for the first time was part of the fun.

## Conclusion

This has been a general survey of points of interest in ram-jet development. In the past six years this new power plant has been brought to the production stage and, I think, stands roughly where the turbo-jet stood in 1945:—Just going into production on an early application with its future position in the propulsion field being worked out as supersonic aircraft begin to emerge, able to exploit its properties of low weight, low cost, high power and good economy.

# TECHNICAL NOTES

## *Spiral and Elliptical Orbits*

by

REAR-ADMIRAL BRIAN EGERTON, R.N. (Retd.)

AN ARTIFICIAL SATELLITE set to start on a circular orbit round the Earth, will have to be given a known velocity, at right angles to the radius vector, which depends upon its distance from the Earth's centre.

It will, from the start, begin to spiral downwards towards the Earth, owing to the resistance of the atmosphere, but if it begins its path at a sufficiently high altitude, the decrease of height after one revolution will be small.

Should the initial "tangential" velocity be greater than the value calculated for a circular orbit, the satellite will, according to the text books, describe an ellipse instead of a circle; and, if at a sufficient distance for the air resistance to be at first ignored, will return after one revolution to the distance at which it started, this point being the perigee of the ellipse. It will never return to a point *outside* the starting point.

If it be found by observation that, instead of doing this, the satellite begins to spiral *outwards*, returning after one revolution to a distance greater than when it started on its orbit, its remarkable behaviour will be explained by those who hold that the text books must be right, as due to "anti-gravitation" or "negative friction," or a combination of both, or some other mysterious cause invented for the occasion.

My prediction is that this is just what it *will* do. In particular, a satellite set to start in a circular orbit at about 7,000 kilometres from the Earth's centre, or about 700 k.m. from its surface, will need a speed of about $7\frac{1}{2}$ k.m. per second. If instead of this speed it is given 8 k.m. per second at that distance, after one revolution it will be farther away than from where it started, travelling in a spiral which will approach a circle at about 1,460 k.m. from the surface.

Before this prediction is condemned as idle nonsense, attention is invited to the following points:—

(1) Corresponding to any elliptical orbit there are spiral curves which are asymptotic to the ellipse, *i.e.* approximating to it as time increases without limit.

(2) Depending upon the conditions, the spiral may be so close to the ellipse as to be indistinguishable from it by observation, even after many years.

(3) Kepler's laws are empirical, and in view of (2) are compatible with either ellipses or spirals-near-ellipses.

(4) The distinction between ellipse and spiral-near-ellipse was not noted by Newton, otherwise he would certainly have mentioned it in the *Principia*. He therefore described the orbits of the planets as ellipses. The only spirals he mentions are logarithmic spirals.

(5) Since his time it has become axiomatic that all gravitational orbits are ellipses, and text books on the "dynamics of a particle" are based on this assumption. They are not a safe guide to what happens in Nature.

*Received 15th April 1957.*

(6) In *any* path subject to a central acceleration, equal areas are swept out in equal times. This is in accordance with the constancy of angular momentum (when undisturbed by other bodies), and may be expressed as $\omega r^2 = \text{constant}$, where $\omega$ is the angular velocity at distance $r$ from the centre of acceleration. (Kepler's second law.)

(7) The total radial acceleration in *any* path is

$$\frac{d^2r}{dt^2} = -\rho + \omega^2 r.$$

This consists of two distinct and independent parts:—

(*i*) Acceleration $-\rho$ towards the centre, due to gravitation only, and independent of any motion the body may have.

In Nature, $\rho = \dfrac{MG}{r^2}$, where $M$ is the mass of the central body, and $G$ is the "gravitational constant," which has the dimensions $L^3 . M^{-1} . T^{-2}$. $\rho$ is proportional to the inverse *square* of $r$.

(*ii*) Acceleration $+\omega^2 r$, away from the centre, due to inertia only, and independent of any acceleration towards the centre.

Since $\omega r^2$ is a constant, $= \lambda^2$ (say), $\omega^2 r = \lambda^2 / r^3$.

It is proportional to the inverse *cube* of $r$. (This important fact is ignored in the text books.)

(8) The total or net acceleration is therefore

$$\frac{d^2r}{dt^2} = \frac{-\mu r + \lambda^2}{r^3} \qquad \text{where } \mu = MG.$$

$\dfrac{d^2r}{dt^2}$ is not generally $= 0$, and the normal path is some sort of *spiral*.

When $\lambda^2$ is greater than $\mu r$, the spiral trends *outwards*, so that $r$ increases until, as time increases without limit, $r$ reaches the value $r_f$ such that $\mu r_f = \lambda^2$. That is, $r_f = \lambda^2 / \mu$. The spiral trends inwards when $\lambda^2$ is less than $\mu r$.

(9) If a satellite be started at distance $r_0$ from the centre in a path at right angles to the radius vector with velocity $v$ it will describe a spiral asymptotic to a circle of radius $r_f$ given by $r_f = v^2 r_0^2 / \mu$.

Only if $v^2 r_0 = \mu$ (*i.e.* $v = \sqrt{(\mu / r_0)}$) will it remain in a circular orbit.

For the Earth, if $r$ is measured in kilometres and $v$ in kilometres per second,

$$\mu = MG = 4 \times 10^5 \text{km}^3\text{sec}^{-2}.$$

For those who are thinking about future navigation in space, it will be vital to know whether my prediction is justified or the text books are right. It is therefore most fortunate that opportunity will arise during the International Geophysical Year to decide by observation. It only requires that some of the artificial satellites shall be released with tangential velocity (at right angles to the

radius vector to the Earth's centre) a reasonable amount, say 15 per cent, in excess of that required for a circular orbit. This could be arranged, although it is almost certain to happen anyhow!

I say *excess*, because that would decide definitely. If the velocity were in defect, the spiralling I predict might be confused with the spiralling due to air friction and written off by altering the formulae for expected effects of the latter.

For the sake of simplicity, I have not referred to any *radial* velocity a satellite may have when set free. It transforms the initially circular orbit into an elliptical one, and its effect is periodic: not continuous as that of tangential velocity.

Remarks on the shape of the orbit for different radial and tangential velocity follow:—

A satellite is supposed to have been set at a distance $r_0$ from the Earth's centre so as to have an angular velocity $\omega_0$ and a radial velocity $u_0=0$. The tangential velocity is $v_0=\omega_0 r_0$. $r_0$ is great enough for the friction of the air to be, at first, ignored.

Then, whatever the orbit may subsequently be, the angular momentum is constant, so that $\omega_0 r_0^2=\lambda$ (constant), $v_0 r_0=\lambda$, $\omega r^2=\lambda$ for all values of $\omega$ and $r$.

The acceleration at $r_0$ is $\dfrac{d^2r}{dt^2}=-\dfrac{\mu}{r_0^2}+\dfrac{\lambda^2}{r^3}$,

the minus sign indicating towards the Earth's centre. $\mu=MG$, $M$ being the Earth's mass, and $G$ the constant of gravitation.

If $\omega_0$ is such that $\dfrac{d^2r}{dt^2}=0$, the orbit is circular and $\dfrac{dr}{dt}=0$. Then $\mu r_0=\lambda^2=v_0^2 r_0^2$, so that $v_0^2=\dfrac{\mu}{r_0}$. But if $\dfrac{d^2r}{dt^2}$ is not equal to 0, suppose $\dfrac{\lambda^2}{r_0^3}$ is greater than $\dfrac{\mu}{r_0^2}$.

$$\frac{d^2r}{dt^2}=\frac{-\mu r_0+\lambda^2}{r_0^3}$$

and the orbit is some sort of *spiral*, outwards. The distance $r$ will increase from $r_0$ with decreasing acceleration to a final value (in infinite time) $r_f$ given by

$$\mu r_f=\lambda^2 \text{ or } r_f=\frac{\lambda^2}{\mu}.$$

The final velocity $v_f$ will be such that $\lambda=v_f r_f=v_0 r_0$ or $v_f=v_0\cdot\dfrac{r_0}{r_f}$.

The polar equation for the spiral is given by

$\dfrac{r_f}{r}=1+be^{-\theta}$ where $r_f=\dfrac{\lambda^2}{\mu}$ and $b$ is a constant.

Differentiating with respect to time:—

$$-\frac{r_f}{r^2}\cdot\frac{dr}{dt}=-be^{-\theta}\frac{d\theta}{dt}:\frac{d\theta}{dt}=\omega \text{ and } \omega r^2=\lambda$$

so that $$-r_f\cdot\frac{dr}{dt}=-\lambda be^{-\theta}$$

and $$-r_f\cdot\frac{d^2r}{dt^2}=\lambda\omega be^{-\theta}=\frac{\lambda^2}{r^3}(r_f-r)$$

$$-\frac{d^2r}{dt^2}=\frac{-\lambda^2}{r_f r^2}+\frac{\lambda^2}{r^3}$$

Since $r_f=\dfrac{\lambda^2}{\mu}$, $-\dfrac{d^2r}{dt^2}=\dfrac{-\mu}{r^2}+\dfrac{\lambda^2}{r^3}$.

If $r=r_0$ when $\theta=0$, $\dfrac{r_f}{r_0}=1+b$, and $b=\dfrac{r_f-r_0}{r_0}$.

For given values of $\omega_0$, $r_0$, $M$ and $\mu$, $\lambda$ and $r_f$ can be calculated, and the curve plotted.

It will be noted that there is a parallel with the ellipse:

$$\frac{r_f}{r}=1+\tfrac{1}{2}b\,(e^{i\theta}+e^{-i\theta})=1+b\cos\theta.$$

In this case $r_f$ is the semi-latusrectum and $b$ the eccentricity. $r_0$ is the distance at perihelion. $b$ as before $=\dfrac{r_f-r_0}{r_0}$.

*(Correspondence on this Technical Note is invited. Rear Admiral Egerton retired from the Navy in* 1935 *after a distinguished career which included serving on the Mining Staff at the Admiralty* 1918, *in the Experimental Torpedo Office, H.M.S. Vernon,* 1920, *and as Director of Torpedoes and Mining at the Admiralty* 1928. *He was recalled in* 1939 *and for the next four years commanded H.M.S. Vernon, Torpedo, Mining and Electrical Training Establishment.—Editor.)*

# *Note on the Drag Due to Lift of Slender Wings*

by

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SEVERAL ATTEMPTS have been made lately to reduce the drag due to lift of wings by means of camber and twist. Slender wings in particular have been considered and a typical theory is that by Tsien[1] on the supersonic conical wing of minimum drag, where the lift forces on the wing are calculated from conventional aerofoil theory so that the overall lift of a flat wing turns out to be proportional to the angle of incidence. For convenience, this is called a "linear theory." It is usual to consider two cases: (1) Wings where the drag is calculated by the same theory so that the full thrust component and the suction at the leading edge are included. (2) Wings where the drag is not calculated by the same theory as the lift but where the thrust at the leading edge is omitted. In the first case, the flow may be interpreted as separating from the trailing edge only and the results usually indicate that little or no improvement over a flat wing can be achieved by means of camber and twist; in the second case, the flow is usually interpreted as incorporating separation from all edges and substantial drag reductions have been predicted. It is the purpose of this note to show that the results in the second case are based on an unrealistic comparison and are therefore misleading. What is not disputed, however, is that it should be possible to design, for one angle of incidence, a cambered wing without flow separation, *i.e.* with the attachment line along the leading edge so that

*Received 25th March 1957.*

the full thrust force but no suction at the actual leading edge is obtained, together with a lift force as from linear theory, in which case the induced drag approaches the classical minimum value.

The error in the argument arises from the idea that the lift of a wing with leading edge separation can be calculated from a theory which assumes a type of flow with trailing edge separation only (*i.e.* in which the trailing vortex sheet is plane and originates only from the trailing edge). In reality, the loss of leading edge suction on wings with highly swept leading edges implies the formation of vortex sheets which coil up above the wing surface and are no longer plane; thus the trailing vortex sheet springs from all edges in this case. As a result, the lift is increased beyond the value corresponding to trailing edge separation only, and a required lift force is produced at a smaller angle of incidence. Hence, even if the resultant air force is normal to the (plane) wing surface, so that the drag due to lift (ignoring the zero-lift drag) is

$$C_D = C_L \alpha, \quad . \quad . \quad . \quad (1)$$

this drag is smaller than

$$C_D = K \frac{C_L^2}{\pi A} \quad . \quad . \quad . \quad . \quad (2)$$

with $K=2$, which is the drag obtained from the slender-wing theory of R. T. Jones[2] when the leading edge suction is omitted but the lift left unchanged. In the latter case, the lift curve is still linear. With the leading edge separation, however, a non-linear lift increment is added to the basic "linear" lift, and the drag may actually be lower than the smallest possible drag obtained from equation (2) with $K=1$. In order that

$$C_L \alpha = \frac{C_L^2}{C_L/\alpha} < \frac{C_L^2}{\pi A},$$

we must have

$$\frac{C_L}{\alpha} > \pi A = 2\left(\frac{C_L}{\alpha}\right)_{\text{R. T. JONES}} \quad . \quad . \quad (3)$$

*i.e.* as soon as the non-linear part of the lift exceeds the linear part, the drag begins to drop below the classical minimum value.

The physical explanation of this important result is that, compared with the flow with trailing edge separation only, the presence of the coiled vortex sheets above the wing enables the wing to generate a given lift force by the deflection downwards of a greater quantity of air at a lower rate.

To get a rough estimate of this drag reduction due to non-linear lift, we may consider incompressible flow and assume

$$C_L = \frac{\pi}{2} A \alpha + 2\alpha^2 \quad . \quad . \quad . \quad (4)$$

so that

$$K = \frac{2}{1 + \frac{4}{\pi}\frac{\alpha}{A}} = \frac{2}{1 + \frac{1}{\pi}\frac{\alpha}{\beta}}, \quad . \quad . \quad (5)$$

if we consider delta wings of semi-apex angle $\beta$. Thus $K \leqslant 1$ when $\alpha \geqslant \pi\beta$ and $K \leqslant 2$ when $\alpha \geqslant 0$. Note that $K$ is no longer independent of $\alpha$. If the drag due to lift as calculated from equation (1), with $K=2$ and $C_L$ from linear theory is $C_D'$, then the real drag, $C_D$, is smaller than $C_D'$ by a factor

$$\frac{C_D}{C_D'} = \frac{1}{1 + \frac{1}{\pi}\frac{\alpha}{\beta}}. \quad . \quad . \quad . \quad . \quad (6)$$

This drag reduction may be considerable and some numerical values from equation (6) are given in column (*a*) of the table below.

| | (*a*) | (*b*) |
|---|---|---|
| $\frac{\alpha}{\beta}$ | $\frac{C_D}{C_D'}$ | $\frac{C_D}{C_D'}$ |
| 0 | 1 | 1 |
| $\frac{1}{2}$ | 0·86 | 0·77 |
| 1 | 0·76 | 0·71 |
| 2 | 0·61 | 0·65 |
| 3 | 0·51 | 0·61 |
| 4 | 0·44 | 0·59 |
| 5 | 0·39 | 0·58 |

This table also contains values, in column (*b*), which have been obtained from the theory of Ref. 3, where the non-linear lift increment is calculated more accurately than by equation (4). Although there are differences between the two estimates, what matters here is that both lead to a substantial drag reduction. How far this can be made use of in practice is a different matter because the maximum value of $L/D$ may occur at a $C_L$-value where the benefit from the leading edge separation is not yet very pronounced.

In conclusion, it follows that any method whereby camber and twist are determined by the second of the foregoing ways—for instance, by "optimising" the drag due to lift ($D'/L^2$) with leading edge suction omitted but a lift force as obtained by linear theory—may give seriously misleading results.

REFERENCES

1. TSIEN, H. S. (1955). The Supersonic Conical Wing of Minimum Drag. *Journal of the Aeronautical Sciences*, Vol. 22, p. 805, December 1955.
2. JONES, R. T. (1946). Properties of Low-Aspect-Ratio Pointed Wings at Speeds Below and Above the Speed of Sound. N.A.C.A. Report No. 835, 1946.
3. KÜCHEMANN, D. A Non-Linear Lifting-Surface Theory for Wings of Small Aspect Ratio with Edge Separations. Unpublished M.O.S. Report.

# *Two-Dimensional Bow Shock Wave Detachment Distances*

by

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THE PURPOSE of this note is to state, briefly, the results of a shock wave detachment study made by means of the hydraulic analogy. A description of the experimental equipment and some details of the work have been given in Ref. 1, where it is shown under what conditions the hydraulic analogy may be considered as a distorted dissimilar model of a corresponding air flow. (*See* also Refs. 2 and 3.)

*Received 8th March 1957.*

## 1. INTRODUCTION

In the recent paper by Warren[4] a summary was made of current data on two-dimensional bow shock wave detachment distances. It was shown that the experimental results of Griffith[5] and Alperin[6], as well as the detachment distances computed by Vincenti and Wagoner[7], could be collapsed into a single curve by using Spreiter's Transonic Similarity Parameter[8]. This has been confirmed by the present authors who have found that the experimental results for wedges obtained by Bryson[9] also correlate favourably with the curve given by Warren (Fig. 3 of Ref. 4).

The results of the foregoing workers have been for steady flow conditions. However, it has been noted by Lilley *et alia*[10] that a steady shock wave pattern can be established in free flight only after steady motion has been maintained for a considerable (infinite) time. In general, the locus of detached bow shock waves depends on the time history of the motion whenever a body is accelerated from subsonic speed. This appears to be the reason for the lack of success in predicting two-dimensional bow shock wave detachment distances by means of the "towed model" hydraulic analogy. Due to the restricted length of existing analogy towing tanks it has been usual to bring the model to the desired speed with a large initial rate of acceleration over a short distance. The model has then been towed at constant velocity for the remainder of its travel, presumably under steady flow conditions. There is evidence in nearly all (towed model) analogy studies made up to the present time that the final flow conditions have *not* been steady (*see* for example Refs. 11-13) and that the results have *included* the influence of the initial acceleration and the history of the motion;* naturally such results have not compared favourably with steady flow gas dynamics data.

To study the effect of acceleration the analogy tank in the New South Wales University of Technology was constructed in such a way that models can be towed either at constant velocity or with uniform rates of acceleration (retardation), over a range of the acceleration parameter $0{\cdot}01 \leqslant \beta \leqslant 1$ where

$$\beta = \frac{al}{C^2}$$

- $a$ acceleration (retardation),
- $l$ chord length of model (approximately one foot in the present case),
- $C$ velocity of surface wave propagation, $\sqrt{(gh_0)}$,
- $h_0$ undisturbed free stream water depth,
- $g$ gravitational acceleration.

The experiments now reported were of an exploratory nature to determine the feasibility of evaluating the effects of acceleration on detachment distance. Although the results are not conclusive, they are sufficiently promising for the study to be continued and indicate that in some cases it may be possible to use the analogy in lieu of free flight tests to study accelerated and retarded motion quantitatively.

## 2. DETAILS OF EXPERIMENTS

The results shown in Fig. 1 were obtained in the series of *ad hoc* experiments described in the following paragraphs. In all cases the models were towed at zero incidence in 0·200 in. deep water. The sides of the models and water surface were treated, as described in Ref. 14, to minimise the influence of surface energy.

*Experiment 1:* A double wedge symmetrical aerofoil of 11·7 in. chord and 1·125 in. maximum thickness was towed in the tank. The tank was fitted with wave traps along the side walls to suppress wave reflections and ensure that choking could not occur. The model was accelerated to steady velocity from rest with a high initial acceleration ($\beta >> 1$) thereafter travelling at constant speed for a distance of approximately 8 ft. (equivalent to about 10,000 ft. in air) before the bow shock wave detachment distance was recorded.

*Experiment 2:* A 20° wedge of 12 in. chord was towed without wave traps being fitted along the side walls of the tank. The history of the motion, up to the point of recording the detachment distance, was identical with that of the double wedge aerofoil in Experiment 1.

*Experiment 3:* The 20° wedge was towed with the wave traps fitted along the side walls of the tank. The history of the motion was the same as in Experiments 1 and 2. Differences between the results obtained in Experiments 2 and 3 were found to be due to an effective reduction in the width of the tank brought about by reversed flow just outside the wave traps.*

*Experiment 4:* The 20° wedge was towed without wave traps fitted along the side walls. In this case the model was initially accelerated from rest to a subcritical (subsonic) velocity. Following this it was given a uniform rate of acceleration to bring it to supercritical (transonic) velocity. After the desired final speed was attained the model was allowed to travel at constant velocity for a distance of approximately four feet (equivalent to about 5,000 ft. in air) before the bow shock wave detachment distance was recorded. This constant velocity motion was necessary so that a quasi-stationary state would be obtained to permit transfer of hydraulic data to air flow conditions following the method stated in Ref. 3, but using Spreiter's parameter.

Due to difficulties in operating the tank, which is rather short, an identical time history was not always obtained. In some cases the initial subcritical velocity was varied in order to maintain $\beta$ constant, while in others the period over which the subcritical speed was maintained varied. The range of the acceleration parameter $\beta$ was from 0·7 to 0·8 approximately.

*Experiment 5:* The 20° wedge was towed as in Experiment 4 with $\beta$ maintained approximately 0·6 and the initial subcritical velocity was varied to permit a final travel at steady supercritical speed of approximately 4 ft. before recording the data.

*Experiment 6:* A 9° wedge of 15 in. chord was towed. Wave traps were not fitted along the sides of the tank and the history of the motion was identical with that obtained in Experiments 1 and 2. The fact that the three points, shown in Fig. 1, plot high was due to difficulties experienced in recording the location of the weaker detached surges: the results have been included only to show that the distorted dissimilar modelling technique will collapse experimental data for considerable changes in thickness ratio if accurate experimental results can be obtained.

*On page 18 of Ref. 13 it was stated that the bow surges "may not have reached an equilibrium position at the time of recording the experimental data."

*As a matter of interest, the wave traps were found to act as a "spongy" wall which energised the water at the sides of the tank and thus eliminated choking. Wave reflection was suppressed due to attenuation within the traps. The thickness of the 20° wedge in relation to the width of the tank without wave traps (1:9·5) was found to give the maximum solid blockage which still produced satisfactory results. When the wave traps were fitted the effective blockage was in excess of 1:8·5.

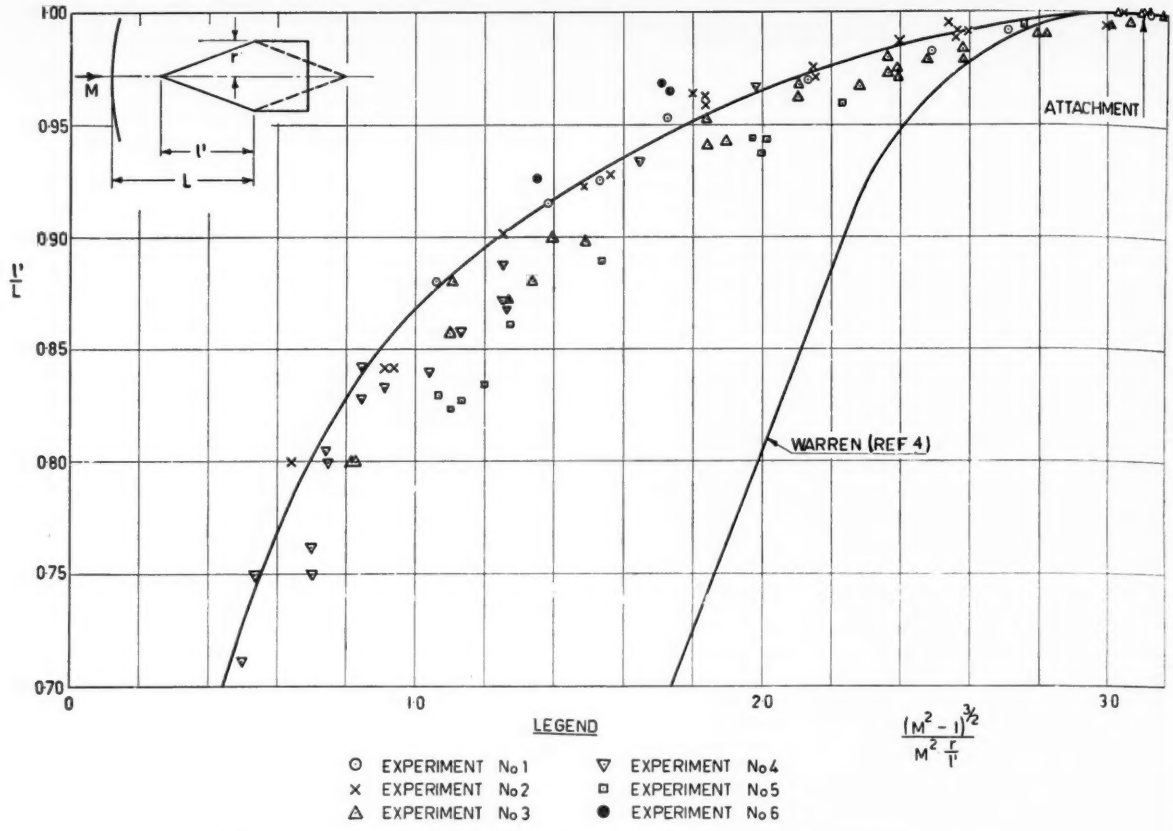


FIGURE 1. Experimental detachment distance as function of Spreiter's parameter (for air).

## 3. COMMENTS

As will be seen from Fig. 1 the results obtained are considerably different from those given by Warren, except in the range near shock attachment.

It is anticipated that experiments conducted with better control in a longer analogy tank would permit a definite evaluation of the influence of acceleration on bow shock wave detachment distances. However, further fundamental work on the analogy is required before the history of the accelerated motion of a model in shallow water can be transferred quantitatively to a corresponding history for a similar affine shape in free flight.

The fact that the experimental value of the similarity parameter at shock attachment is the same as for steady flow bears out the work of Rao[15] who has shown that the shock conditions are then independent of acceleration.

## 4. ACKNOWLEDGMENT

The authors thank Dr. L. C. Woods, Nuffield Research Professor in Mechanical Engineering, for his interest in the hydraulic analogy research programme.

## REFERENCES

1. BRYANT, R. A. A. (1956). A Study of the Transonic Gasdynamics Analogy, 184 pp. and 55 Figs. The N.S.W. University of Technology, December 1956 (Unpublished).
2. BRYANT, R. A. A. (1956). The One-Dimensional and Two-Dimensional Gasdynamics Analogies. *Australian Journal of Applied Science*, Vol. 7, No. 4, pp. 296-313, Dec. 1956.
3. BRYANT, R. A. A. (1956). The Hydraulic Analogy as a Distorted Dissimilar Model. *Journal of the Aeronautical Sciences*, Vol. 23, No. 3, p. 282, March 1956.
4. WARREN, C. H. E. (1956). Recent Advances in the Knowledge of Transonic Air Flow. *Journal of the Royal Aeronautical Society*, Vol. 60, No. 544, April 1956.
5. GRIFFITH WAYLAND (1952). Shock Tube Studies of Transonic Flow Over Wedge Profiles. *Journal of the Aeronautical Sciences*, Vol. 19, No. 4, April 1952.
6. ALPERIN, M. (1951). A Study of Detached Shock Waves due to Supersonic Motion of Two-Dimensional Bluff Bodies. California Institute of Technology, Jet Propulsion Laboratory Report 20-60, November 1951.
7. VINCENTI, W. G. and WAGONER, C. B. (1952). Transonic Flow Past a Wedge Profile with Detached Bow Wave N.A.C.A. Report 1095, 1952.
8. SPREITER, J. R. (1954). On Alternative Forms for the Basic Equations of Transonic Flow Theory. *Journal of the Aeronautical Sciences*, Vol. 21 No. 1, January 1954.
9. BRYSON, A. E. (1952). An Experimental Investigation of Transonic Flow Past Two-Dimensional Wedge and Circular-Arc Sections Using a Mach-Zehnder Interferometer. N.A.C.A. Report No. 1094, 1952.
10. LILLEY, G. M., WESTLEY, R., YATES, A. H. and BUSING, J. R. (1953). Some Aspects of Noise from Supersonic Aircraft. *Journal of the Royal Aeronautical Society*, Vol. 57, No. 510, pp. 296-414, June 1953.
11. LAITONE, E. V. (1950). An Experimental Investigation of Transonic and Accelerated Supersonic Flow by the Hydraulic Analogy. University of California Institute of Engineering Research, Series 3, No. 315, July 1950.
12. LAITONE, E. V. (1952). A Study of Transonic Gas Dynamics by the Hydraulic Analogy. *Journal of the Aeronautical Sciences*, Vol. 19, No. 4, April 1952.
13. CROSSLEY, H. E. and HARLEMAN, D. R. F. (1952). Studies on the Validity of the Hydraulic Analogy to Supersonic Flow, Part 5. Towed Model Investigation of Transonic Flow, Massachusetts. Institute of Technology, Hydrodynamics Laboratory, Tech., Report No. 11, Dec. 1952.
14. BRYANT, R. A. A. (1956). Some Comments on Surface Contamination in Hydraulic Analogy Research. *Journal of the Aeronautical Sciences*, Vol. 23, No. 11, Nov. 1956.
15. RAO, P. SAMBASIVA (1956). Supersonic Bangs, Part I. *The Aeronautical Quarterly*, Vol. 7, Part I, Feb. 1956.

# Graduates' and Students' Section

## Guided Weapon Research and Development

A fascinating lecture on guided weapons in the past, present and future was given on the 15th May by Mr. W. H. Stephens, M.Sc., A.F.R.Ae.S., Deputy Director of the Royal Aircraft Establishment.

The talk opened with an historical survey. Unguided rockets have a long history, being used operationally in the 19th century. Pioneer work before the war was done on liquid fuel rockets by Goddard in the U.S. and Oberth and Sanger in Germany. Unmanned aircraft were built in Britain and the U.S.—the British Larynx flying bomb was developed in the late twenties.

During the war considerably more work was done in both Germany and the United States than in Britain. Germany was foremost by far and developed a wide range of weapons, the most successful being guided anti-shipping bombs and the V.1 and V.2. Accuracy of the V.2 was unequalled for a decade. German development of ground-to-air missiles did not achieve great success, however.

In the United States there was concentration on guided bombs and a certain amount of basic work was done on artillery rockets.

Guided weapons fall naturally into four groups: air-to-air, surface-to-air, air-to-surface and surface-to-surface.

In general, air-to-air weapons are lighter than the others, have a shorter range and must be able to home on to a manoeuvrable target. The fighter from which they are launched must be associated with a good ground radar system.

Surface-to-air weapons must have a longer range, and, of necessity, be supersonic if they are to be effective.

Air-to-surface weapons are usually either supersonic or in the high-subsonic category.

Surface-to-surface missiles fall into two main groups: the high-subsonic or supersonic unmanned aircraft and the true ballistic missile.

There are four main types of guidance system used for anti-aircraft missiles. The first is command guidance, in which separate radars track target and missile and the missile receives guidance on the course necessary for interception. A second system is semi-active homing in which the missile homes on the reflections from the target of a radar beam transmitted from a ground station or from the launching aircraft. A third system is active homing in which the missile carries both a radar transmitter and receiver, homing on the reflections from pulses which it transmits. The fourth system, beam riding, is self-explanatory; a radar beam tracks the target and the missile travels within the beam until it intercepts the target.

A typical weapon has a cruciform wing and cruciform control surfaces to give it rapid control response—a two-winged weapon has to roll and bank to change direction and cannot compete with one of cruciform layout unless it has a very high rate of roll; this demands very powerful, and thus heavy, actuators.

The technical problems of a missile are closely inter-connected; they involve structures, propulsion, aerodynamics, and auto-pilot and homing systems as well as practical matters such as ground-handling, testing, and so on.

On launching, missiles are usually boosted to supersonic flight. Stability is a problem; in both the boost and flight phases the weapon must have weathercock stability. A compromise is essential on stability, as the missile must be both stable yet possess considerable power of manoeuvre. Typical missiles are roll-stabilised. A well-damped manoeuvre response is essential and feed-back damping is used.

It is of great assistance if these problems can be simulated electronically; parameters can easily be varied and their effect studied.

In the development of a missile a vast amount of wind tunnel, simulator work and flight testing must be carried out. Engineering problems created by vibration and heating are acute. Boost-phase acceleration can be up to 40*g* and vibration accelerations up to 100*g*. There are sometimes transient effects when the boost motors separate.

The installation of power plants meets the difficulties of installing the fuel tanks and pumping systems with liquid-fuel motors and of strength requirements for solid-fuel motors. Variations of the c.g. as fuel is consumed and the centre of pressure with Mach number must be allowed for. Structural oscillations and flutter may cause difficulties. Accelerometers and gyros must be suitably located within the weapon so that their performance is not adversely affected by vibrations.

In general it is the system concept which decides all aspects of the design of a weapon.

### *The Future*

Scientific work in future will be greatly helped by upper-atmospheric rockets, such as the British Skylark, and Earth-satellite vehicles; both will be used for scientific work during the International Geophysical Year.

A three-stage rocket will be used to launch the satellite. The first two stages will be fired consecutively, after which the vehicle will coast until it is travelling at a tangent to the planned orbit, when the third stage will be fired to accelerate it to orbital velocity.

The problem of the intercontinental ballistic missile is similar to that of the satellite. With the I.B.M. more accurate control is essential, as it must be guided to achieve a precise velocity in a precise direction at the end of the propulsion phase if it is to be accurate. Thereafter it coasts over by far the greater part of its range to the target.

A typical I.B.M. would travel 5,000 miles in 30 minutes, reaching a peak altitude of 500 miles. It would re-enter the atmosphere at 16,000 m.p.h. and must of necessity be slowed down before entering the lower atmosphere if it is not to burn up.

A long-range ballistic rocket will have a take-off weight about 50 times that of its payload—a fact that augurs ill for space travel, even to such nearby bodies as the moon. Space travel will come, but facts such as this mean it will be exceedingly expensive. One of its main problems will be navigation. Long travel-durations are likely and navigation may depend on gyros whose error varies with time and in some cases the square and cube of time.

J.R.C.

## R.A.E. Rocket Propulsion Department—VISIT

There are still some vacancies for the visit to the R.A.E. Rocket Propulsion Department at Westcott, Bucks, on Wednesday 10th July. A coach has been hired which will leave Central London at 11.30 a.m.

As this should be a most interesting visit and arrangements have to be completed with the R.A.E., will those who wish to make this visit please write at once to the Hon. Visits Secretary, Mr. N. K. Benson, 14 Wakering Road, Barking, Essex.

# THE LIBRARY

## *Reviews*

ENGINEERING ANALYSIS (*A Survey of Numerical Procedures*). *S. H. Crandall. McGraw-Hill, New York, 1956. 417 pp. Illustrated. 71s. 6d.*

This is essentially a book on numerical analysis. It differs from most books on this subject, however, in that examples taken from various branches of engineering are used to set each type of numerical problem in its physical context. The first half of the book is devoted to the analysis of discrete systems and the second to continua. Each half is divided into three chapters dealing with equilibrium, eigenvalue, and propagation problems respectively, while each chapter is prefaced by a number of physical examples.

The first chapter considers the solution of sets of simultaneous algebraic equations, the emphasis being on linear systems. While iterative and relaxation methods are developed in some detail the treatment of exact procedures is extremely sketchy. The account of matrix algebra, with which Chapter 2 opens, might have been better placed at the beginning of Chapter 1.

The second chapter provides a comprehensive survey of both exact and iterative methods for solving matrix eigenvalue problems. It concludes an account of some recently developed exact processes, such as that of Lanczos, which have proved particularly suited to automatic computers.

Propagation problems in discrete systems give rise to sets of ordinary differential equations with one-point boundary conditions, and these are considered next. The author describes methods based on continuous function approximations as well as finite-difference techniques, and gives a useful account of the truncation errors and stability of the various step-by-step processes.

The second half of the book deals with elliptic, parabolic, and hyperbolic partial differential equations. Methods using continuous function approximations are considered, as well as relaxation and other finite difference techniques. Chapter 4 includes an account of the calculus of variations, while Chapter 6 contains a clear summary of the method of characteristics.

As the introduction suggests, this book is a catalogue of numerical techniques. It covers a very wide field, with the inevitable result that many topics are treated more briefly than would be suitable in a self-contained textbook. In some cases methods are merely mentioned by name and a reference given, while in others the discussion is so condensed as to require considerable effort on the part of the reader. A large number of exercises are provided and there are copious references to books and original papers.

When compared with pre-war textbooks on engineering mathematics, this book shows a significant change in the mathematical equipment thought suitable for an engineer. Not only does Professor Crandall expect his readers to be mathematically adult and familiar with the normal language of applied mathematics. More important, he shows that by looking at engineering systems with the eye of a mathematician, many apparently disconnected problems can be seen to fit into an orderly pattern. While one may criticise his treatment of certain numerical techniques it is this sense of pattern which makes his book an important one for theoretical engineers.—R. K. LIVESLEY.

SELECTED COMBUSTION PROBLEMS. II. *Transport Phenomena; Ignition; Altitude Behaviour and Scaling of Aero-engines. Senior Editor M. W. Thring. Agardograph. Butterworths Scientific Publications, London, 1956. 495 pp. Illustrated. 90s.*

This volume contains eighteen review papers presented at the second AGARD Combustion Colloquium held at Liège in December 1955, together with written contributions to the discussion and the authors' replies. The emphasis is on the application of fundamental combustion theory and the analysis of experimental data to jet aero-engine design and development. Three papers concern liquid-fuelled rocket motor problems.

The conjunction of papers on fundamental combustion studies and related topics with those on combustion problems in engines should be a very fruitful one, particularly for those who, mainly concerned with one side, wish to learn something of what is happening on the other. The value of the book as a whole is very much due to the inclusion of the written contributions to the discussion together with the authors' replies. The overall standard of the papers is high but they could with advantage have been reduced in number and, in many cases, in length.

The first section, one which is not explicitly mentioned in the sub-title, is Aircraft Engines and Fuels. It contains two papers, one of which discusses the performance characteristics of jet engines and the other, the properties of hydrocarbon fuels and their influence on the performance and operational problems of engines. The second section on Ignition and Flammability deals mainly with fundamental aspects and starts with a review of flame stability theory, limits of inflammability and ignition theory by Lewis and von Elbe which, in the discussion section, provokes an interesting discussion of the excess enthalpy concept. Two points regarding this paper, which do not appear to have been discussed, are: firstly, that the temperature perturbation of the steady state combustion wave, described by the authors, leads to extinction only if the system can lose heat from the high temperature region by some process such as radiation; secondly, that the existence of a multiplicity of solutions to the steady state flame equations in the case of zero excess enthalpy is not evidence for the necessity of an excess enthalpy wave. Hirschfelder has demonstrated that a range of solutions exists, each being determined by the heat loss at the cold boundary. This is true for all ratios of mass to thermal diffusion. The existence of an apparently unique flame velocity is due to the effective independence of that velocity over large ranges of the heat loss parameter. The solutions corresponding to flow velocities greater than that of the "unique" flame velocity, which satisfy small values of the heat loss parameter, are stable and can be physically interpreted as corresponding to the steady state of inflammation of a reacting gas flow at temperatures above the "spontaneous" ignition temperature and at flow velocities in excess of the flame velocity.

Experimental data on thermal ignition at high temperatures are reviewed by Brokaw who draws attention to the discrepancies between data obtained by different methods. Neither these, nor those between homogeneous reactor combustion times and ignition delay times, is altogether surprising in view of the wide differences between the

conditions of experiment and the criteria of reaction employed. The difficulty of comparing experimental data obtained by different methods, unless the variation and mode of influence of each experimental parameter is well understood, is emphasised by the subsequent sections on altitude and scaling problems in jet engines.

The colloquium and the publications of these papers and discussions will undoubtedly give a strong stimulus to further work and thought. The organisers and the editors of this volume are to be congratulated on having produced this excellent record.—G. K. ADAMS.

EXAMPLES IN MECHANICAL VIBRATIONS. *John Hannah and R. C. Stevens. Edward Arnold, London, 1956. 152 pp. Illustrated. 18s.*

There are seven chapters in this book, each containing a resumé of the theory of a particular topic, a number of worked examples and a much larger number of unworked examples with answers. In general, the questions are of Honours Degree standard, and most of them are taken from past examination papers of the Universities of London and Glasgow and of the Institution of Mechanical Engineers.

Chapter 1 deals with the free vibrations of single and two degree-of-freedom systems, and the worked examples cover the calculations of periodic times, determination of moments of inertia and problems involving coupled pendula and mass-spring systems. Aeronautical engineers may find the use of the term "vibrations per minute" unfamiliar.

The treatment of beam vibrations in Chapter 2 is based on the Energy principle, but exact solutions for the uniform beam and the taut string are given. It is a pity that there is no mention of Rayleigh's method in this chapter, since it is of more general application and more widely known than the method given.

In Chapter 3 the theory of shaft whirling is illustrated with examples on heavy shafts with concentrated loads, the influence of disc slope, and the effects of end thrust.

Torsional oscillations are dealt with in Chapter 4, beginning with single and two rotor systems and leading up to the solution of multi-rotor systems by Holzer's method.

In Chapters 5, 6 and 7, which deal respectively with damped-free, forced-free and forced-damped oscillations, the emphasis is on the solution of the differential equations involved.

Both viscous and Coulomb damping are considered in Chapter 5, the examples being mainly concerned with damped mass-spring systems.

The worked examples in Chapters 6 and 7 are, except for the inclusion of damping, rather similar. Resonance and the effect of periodic movement of the support are considered, and the influence of springs and dampers on engine vibration is illustrated. There are examples on forced torsional oscillations and the energy absorbed by dampers is calculated.

One criticism which can be made of the book as a whole is that the presentation of the worked examples is out of balance. The numerical calculations are set out in considerable detail—in some cases whole pages are taken up with numbers—whereas important formulae are quoted from the text. Some of this is unavoidable, but it may encourage students to remember formulae and not to work from first principles.

But there is no doubt that this book will be of great value to engineering, especially mechanical engineering students, for it is not merely a collection of examples but also a useful supplementary textbook.—J. P. JONES.

METHODS IN NUMERICAL ANALYSIS. *K. L. Nielsen. Macmillan, New York, 1956. 382 pp. 48s. 6d.*

For an author to write a successful book on Numerical Analysis, particularly one of an avowedly practical nature, he must achieve a level of accuracy markedly higher than may be tolerated in other monographs. Above all else his formulae and his examples must be correct, while he has the additional duty of warning his readers of the possible cases in which a given method may break down.

Dr. Nielsen's book unfortunately falls far short of these high ideals. The reader's confidence is severely shaken when he finds that the first difference table contains serious errors and is in any case devoted to divergent differences; one of the most important precepts in computing is that in general only convergent differences should be used, but nowhere is this mentioned. Again the integration formula (42.8) is incorrect and one's first impression that the error might be merely one of transcription is rapidly dispelled by the remark "To better understand formula (42.8) let us indicate clearly in a central difference table which elements are used"; they are indicated clearly, and wrongly, and the result of the example computed is incorrect. In a book of this nature such carelessness is inexcusable.

While it is to the author's credit that he includes numerous worked examples, and is at some pains to consider questions of layout, he often omits to refer to the errors that may arise in the general application of the formulae. For example, there is no reference to the necessity of using as wide an interval as possible when differentiating numerically, and the result of the first example is quoted to one figure more than given in the differences; although it happens to be correct in this case, it is nevertheless misleading.

Many other defects stem from the author's attempting the impossible and including, within a relatively small compass, chapters on Fundamentals, Finite Differences, Interpolation, Differentiation and Integration, Lagrangian Formulae, Ordinary Equations and Systems, Differential and Difference Equations, Least Squares and their Applications, and Periodic and Exponential Functions. While one welcomes the last two chapters the treatment in many others is sketchy in the extreme. Only Crout's method (good, but inferior in layout to those of both Cholesky and Doolittle) is included for the solution of simultaneous equations, and there is no reference to either central-difference or deferred-correction processes for ordinary differential equations; the section on partial differential equations is so condensed as to be practically valueless, the description of the relaxation method being particularly poor. The author could well have saved some space by using operational methods to replace the unwieldy algebra of some of the proofs.

Finally, although the author may consider that the retention of the forward difference notation in central difference formulae avoids unnecessary confusion, in the reviewer it produced a revulsion which coloured his reading of the rest of the book.—E. T. GOODWIN.

PROCEEDINGS OF THE SOCIETY FOR EXPERIMENTAL STRESS ANALYSIS. *Vol. XIII. No. 1. Cambridge, Mass., 1955. 213 pp. Illustrated.*

This number of the Proceedings contains eighteen papers of which the majority are on the use of established methods of stress analysis. An interesting application of electrical resistance strain gauges is in the testing of columns under end load, where they were used not only for measuring curvature during a test but for centering the load initially. Another paper describes a new pressure tank for the testing of model submarine hulls under

external hydrostatic pressure and also the special equipment devised to measure the radial deflections. The description of the combined load testing machine at the Langley Structures Laboratory is also of interest. This machine can apply and measure up to three loads and three moments simultaneously.

On the properties of electrical resistance strain gauges there are investigations of the performance of wire and foil gauges when subjected to oil pressure as well as strain. The gauges recorded strain satisfactorily, the foil gauges under pressures up to 30,000 lb./sq. in., but some unexplained results with the wire gauges need further study. Special gauges for the direct measurement of principal stresses are available commercially but there is here a discussion of the use of a single gauge of conventional type for this purpose. The angle at which the gauge must be set to read either the maximum or minimum principal stress requires a knowledge of the principal stress directions and also of the value of Poisson's ratio for the material under study. For mounting Bakelite type gauges on structural members a special tool is described. It consists of a plunger loaded by air pressure which also contains a heating element; suitable shoes can be made for use on curved surfaces. When a strain gauge of higher sensitivity is needed, the barium titanate ceramic wafer may be used and a paper gives frequency response curves for these gauges. It is shown that, although the sensitivity is constant over the range 20 to 600 cycles per second, there is sufficient variation between gauges to necessitate individual calibration.

In the field of brittle coatings there are two further contributions on the properties of Stress-coat from the Armour Research Foundation. These careful investigations should promote increased interest in the use of this method and this is in fact borne out by the publication of two written discussions on the papers.

Photoelasticity occupies less space than usual in this number of the Proceedings but there is an example of its use for the examination of fillets of such a curvature as to be free from stress concentration. In another paper Neuber's equations are used to show that the distribution of stress at the base of a hyperbolic notch in a round bar subjected to tension, torsion or bending is approximately the same as that for a flat plate. A continuation of this work gives curves for the stress gradient across the narrowed section under the same conditions.

Two papers on electrical analogues are included. One makes use of resistance networks for the study of non-linear problems in vibration and elastic stability and the other represents a mechanical system in terms of inductance, capacity and resistance for the study of transient effects such as those caused by earth shocks generated by explosions and by earthquakes.

There are four other papers. The first describes a method of testing rubbers and plastics under dynamic loading. The sample is placed between two ballistic pendulums, with which striking velocities up to 80 cm./sec. have been reached. Analysis of the results is based on the displacement-time relationship during the impact but it is hoped that more informative results may be obtained by later experiments in which accelerations are to be measured. The second paper discusses methods of tracing the modes of vibration of a vibrating body with a transducer and oscilloscope. The third describes a ballistocardiograph for recording the loads on the body caused by the acceleration of the blood and thus for a study of the action of the heart. The last in this group reviews many of the structural problems confronting the designer of gas turbine engines.—A. F. C. BROWN.

RADIO TELEMETRY. *2nd Edition. M. H. Nichols and L. L. Rauch. Chapman and Hall, London, 1956. 461 pp. Illustrated. 96s.*

In the past few years many published papers have shown the use of particular telemetering techniques in solving a wide variety of problems. Indeed, the present state of aeronautical science is witness to the value of these techniques in one field alone. To the user, on the other hand, the complexity of the technology has made it extraordinarily difficult to judge the relative merits of possible systems. This volume which is a critical survey of the whole field of radio telemetering is therefore particularly welcome.

The book itself falls into three sections, dealing respectively with general methods, basic theoretical relationships and practical techniques. A series of appendices, mainly of a theoretical nature, are also included.

The larger part of the book describing methods begins with a brief historical survey of the science. The philosophy of multiplex working and an introduction to the problem of noise follows, and the effect of different methods of modulation on the radio link are discussed. A chapter on transducers is included.

The second section dealing with theory describes mathematically the features of modulation and multiplexing that are of importance in telemetering. Alternative systems are analysed.

The third part includes detailed descriptions of practical systems which have been used, with circuit diagrams and notes on their operation. A chapter on the reduction of data provided by telemetering systems in general is included. The features of radio control links and their properties are also briefly compared with telemetering channels.

The appendices include details of a variety of important mathematical analyses. A typical example is the short section describing the selection of frequencies for multiplex frequency modulation systems to minimise crosstalk. Details of American standards for telemetering apparatus are also given.

The authors of this book stress the importance of designing as a coherent whole an experiment in which telemetering plays a part. Towards this end they have produced a most lucid guide to the design and construction of such telemetering apparatus. Their book is well illustrated by examples, drawings and photographs, and includes a large bibliography drawn mainly, but not entirely, from American sources. Perhaps the most useful parts of the book are those dealing with the fundamental signal-to-noise relationships inherent in different telemetering systems.

Both telecommunication and aeronautical engineers would undoubtedly find much of value in this volume.—H. A. DELL.

VISION. *A Saga of the Sky. Harold Mansfield. Duell, Sloan and Price, New York, 1956. 389 pp. Illustrated. $5.00.*

Patriotism is splendid by itself and finest of all when expressed with a deep sincerity. Patriotism allied with the humility which acknowledges that one's own country is not the only significant part of the Earth is one of the roots of Wisdom.

Harold Mansfield writes with admirable sincerity about the aims and achievements of his own country but seems often to overlook the existence of others. He has written the history of the Boeing Airplane Company in a most unusual way—told, as the dust jacket explains, in the technique of fiction. The theme of this story is "Honesty

of Purpose" and the author expresses the idea very clearly in his description of the many setbacks which the Company suffered before it reached its present very important position in the aviation industry.

The style of the book is restrained by modern standards of journalism but is tedious in the verbatim conversations which make up so much of its substance. If it were called padding that would be no injustice since the book would be far more valuable if it were compact, concise and half its present size. As a historical work it is of interest nevertheless. ' There are few inaccuracies but the author dabbles in scientific theories without much conviction. It is curious that no reference is made to Boeing's experimental long-range strike fighter which flew in 1946, the XF8B.

The author's quotation of Lincoln " . . . that this nation under God may have a new birth of freedom," is, unfortunately, spoilt by emphasis placed only on the hitting power of the B-47 and B-52 and the moral power of the United States. He makes no mention of the fact that certain other nations, also under God, are working closely with America towards the same ideal—freedom.—A.S.C.L.

CRASH PILOT. *Dick Grace. Longmans, Green, London and New York, 1956 (first published in the U.S.A. under the title "Visibility Unlimited," 1950). 276 pp. 16s.*

Richard V. Grace was born in 1898, the son of an eminent American lawyer. He enlisted in the United States Navy as a pilot at the age of nineteen soon after the entry of America into the First World War and, after service in Europe, he spent several years barnstorming with war-surplus aircraft of doubtful reliability.

Crash followed crash until Grace was destitute of everything but courage. He started anew at Santa Monica in Southern California and, learning much from his involuntary experience in handling aeroplanes with defunct engines, he built up for himself a unique reputation for stunt flying for motion pictures. He devised "safe" methods of crashing aircraft a few feet from cameras involving complete write-offs and somehow survived a broken neck and over eighty other fractures in about fifty deliberate crashes. Each wreck was carefully calculated and carried out without emotion (although sometimes in spite of great pain from previous injuries) so as to give the camera men the shots they needed without involving them in unnecessary risk.

The Second World War started and Dick Grace, well over forty on the entry of the United States into the conflict, determined to see action in Europe. His wangles to get round regulations which should have eliminated him from combat duty due to his age and the physical damage he had suffered previously were characteristic of this determined fighter who knew what he wanted and usually got it. He also got a large piece of German flak in his thigh.

His autobiography is, on the face of it, pure blood and thunder but it is told in an unemotional, detached way which makes interesting reading and the subject matter is most unusual. It is the story of a brave man and not a braggart.—A.S.C.L.

GLOSSARY OF AERONAUTICAL DEFINITIONS: ENGLISH-GERMAN/GERMAN-ENGLISH. *Roderich Cescotti. Hanns Reich Verlag, Munich, 1956. 270 pp.*

This Glossary has been prepared from BS 185 and in parallel columns are the translations both of the term and the explanatory matter. English readers will have to turn to a German index and get the English equivalent from a numerical indicator.

JANE'S ALL THE WORLD'S AIRCRAFT 1956-57. *Compiled and edited by Leonard Bridgman. Assistant Compiler John W. R. Taylor. Jane's All the World's Aircraft Publishing Co. Ltd., 1956. 454 pp. Illustrated. 84s.*

All that is to be said of the latest "Jane's" will already have been said. One can only congratulate the compiler, therefore, on achieving a review on the B.B.C. at 6.30 a.m. on the day of publication, on taking unto himself an assistant of such high calibre, on coining a new word "phenomenal" to describe the success of the Viscount, on receiving a graceful tribute from the publishers in his own book and, finally, on producing, to the same superlative standard, another edition of this unique work. Incidentally, the publishers claim, on behalf of Mr. Bridgman and his predecessor C. G. Gray, that they were the only editors, writers or journalists to receive Paul Tissandier Diplomas. May we put in a claim for our own J.L.P. who was editor of the Journal and is no mean writer.

One cannot review "Jane's" (I have said this before). One can only crib the exciting paragraphs from the compiler's Preface (as most of the reviewers do) and then go on thanking the gods for the rest of the year that you have most of the answers to your queries in one set of volumes. It is expensive, of course, but at the present price anybody who can save 1s. 8d. a week can have his own copy by the end of the year. It is worth it.—F.H.S.

INTRODUCTION TO HELICOPTER AERODYNAMICS. *Revised edition. W. Z. Stepniewski. Rotorcraft Publishing Committee, Morton, Pa., 1956. 257 pp. Illustrated.*

This book is the third in a series of publications sponsored by the Rotorcraft Publishing Committee. The first volume, "Introduction to Helicopter Aerodynamics," by W. Z. Stepniewski, was published in 1950 and the second volume "Helicopter Performance Calculations," by Sloan, Harris and Ulrich, was published in 1952.

The present volume is a combination of the first two, reprinted from them by photo-reproduction, with some additional material on rotor downwash distribution in forward flight, performance of over-lapping rotors in hovering flight, and aerodynamic interference of tandem rotors in forward flight.

ILLUSTRIERTE TECHNISCHE WÖRTERBÜCHER. *Volume XVII. Aeronautics. Alfred Schlomann. R. Oldenbourg. Munich—A Correction.*

It is regretted that the review of this book in the May JOURNAL incorrectly stated that it was a revised edition of that published in 1932. It is, in fact, a reprint. It is hoped that this misinformation has caused readers no inconvenience. Unfortunately there was also a misprint in the title which should be as now given.

ORDINARY NON-LINEAR DIFFERENTIAL EQUATIONS IN ENGINEERING AND PHYSICAL SCIENCES. *2nd edition. N. W. McLachlan. Clarendon Press, Oxford, 1956. 271 pp. Illustrated. 35s.*

The JOURNAL for February 1951 (p. 127) contains a review of the first edition of this book, ending with: "The book is written in a direct and readable style and is clearly intended for the newcomer to the subject who wants to gain a working knowledge of it. As such it can be warmly recommended to all engineering scientists and applied mathematicians."

In addition to much new material, this second edition contains 52 problems, with answers, and 68 additional references. In all, it is increased in size by about a third.

## *Additions to the Library*

Allen, J. A. van (*Editor*). SCIENTIFIC USES OF EARTH SATELLITES. Chapman and Hall. 63s. 1956.

B.E.D.A. INDUCTION AND DIELECTRIC HEATING. ELECTRICITY AND PRODUCTIVITY, SERIES 6. B.E.D.A. 1957.

Beaumont, A. MY THREE BIG FLIGHTS. Eveleigh Nash. 1912.

Biot, M. A. EFFECT OF THERMAL STRESSES ON THE AEROELASTIC STABILITY OF SUPERSONIC WINGS. Cornell Aero. Lab. 1956.

Birkhoff, G. and Zarantonello, E. H. JETS, WAKES AND CAVITIES. Academic Press. 80s. 1957.

Buckingham, R. A. NUMERICAL METHODS. Pitman. 70s. 1957.

Carafoli, E. HIGH-SPEED AERODYNAMICS (COMPRESSIBLE FLOW). Editura Tehnica, Bucharest. 1956.

Cardwell, D. S. L. THE ORGANISATION OF SCIENCE IN ENGLAND. Heinemann. 18s. 1957.

Carter, L. J. (*Editor*). REALITIES OF SPACE TRAVEL. Putnam. 35s. 1957.

Day, J. S. SUBCONTRACTING POLICY IN THE AIRFRAME INDUSTRY. Harvard Business School. 32s. 1957.

Fraser, D. A. S. NONPARAMETRIC METHODS IN STATISTICS. Wiley. 68s. 1957.

Gartmann, H. MAN UNLIMITED (TECHNOLOGY'S CHALLENGE TO HUMAN ENDURANCE). Cape. 18/-. 1957.

Harlan, N. E. MANAGEMENT CONTROL IN AIRFRAME SUBCONTRACTING. Harvard Business School. 32/-. 1957.

Hodgkinson, C. BEST FOOT FORWARD: AUTOBIOGRAPHY OF COLIN HODGKINSON. Odhams. 18/-. 1957.

Ivall, T. E. (*Editor*). ELECTRONIC COMPUTERS. Iliffe. 25s. 1956.

Koelle, H. H. and Kaeppeler, H. J. LITERATURE-INDEX OF ASTRONAUTICS. Walter Pustet. 6.40 DM. 1954.

Lewis, H. T. *et al.* THE ROLE OF AIR FREIGHT IN PHYSICAL DISTRIBUTION. Harvard Business School. 20s. 1957.

Liepman, H. W. and Roshko, A. ELEMENTS OF GASDYNAMICS. Wiley. 88s. 1957.

Maycock, *W. Cdr.* R. DOCTORS IN THE AIR. Allen and Unwin. 15s. 1957.

Minister of Defence. DEFENCE—OUTLINE OF FUTURE POLICY. H.M.S.O. 9d. 1957.

Noton, B. R. HONEYCOMB SANDWICH CONSTRUCTION IN CIVIL AND MILITARY AIRCRAFT. Second European Aeronautical Conference. 1956.

Noton, B. R. SWEDISH AERONAUTICAL RESEARCH ON METALLIC HONEYCOMB SANDWICH CONSTRUCTION. Soc. of Aircraft Materials and Process Engineers. 1957.

Rawnsley, C. F. and Wright, R. NIGHT FIGHTER. Collins. 18s. 1957.

Sänger, E. FORSCHUNG ZWISCHEN LUFTFAHRT UND RAUMFAHRT. Walter Pustet. 3.90 DM. 1956.

Shatz, R. H. THE OBJECTIVES AND TECHNIQUES OF WEAPONS SYSTEMS ANALYSIS (REPRINT OF A SPEECH). Cornell Aeronautical Laboratory. 1957.

Society of Automotive Engineers. AIRCRAFT PRODUCTION (FORUM DISCUSSION). S.A.E. 40s. 1956.

Swiggett, R. L. INTRODUCTION TO PRINTED CIRCUITS. Chapman and Hall. 21s. 1956.

Thetford, O. AIRCRAFT OF THE ROYAL AIR FORCE, 1918-1957. Putnam . 50s. 1957.

Vawter, F. J. *et al.* INVESTIGATION OF THE COMPRESSIVE, BEARING, AND SHEAR CREEP—RUPTURE PROPERTIES OF AIRCRAFT STRUCTURAL METALS AND JOINTS AT ELEVATED TEMPERATURES. WADC Tech. Rpt. 54-270, Part 1 (Photostat). Cornell Aeronautical Laboratory. 1954.

Whipple, F. L. (*Editor*). SMITHSONIAN CONTRIBUTIONS TO ASTROPHYSICS. Vol. 1, No. 1. NEW HORIZONS IN ASTRONOMY. Smithsonian Institute. 12s. 9d. 1956.

Yourieff, B. N. (Trans. by Crean, J. R.). THE SOVIET SCHOOL OF AERODYNAMICS IN THE ACADEMY OF SCIENCES. Academy of Sciences. 1945.

## *S.A.E. Preprints*

81 Large lightweight turbojet engines. C. A. Grinyer.

82 Potential advancements in the field of small aircraft engines. R. V. Hensley *et al.*

83 Introducing new jet engine production with reduced lead times. R. Medros.

84 Problems in the application of high strength steel alloys in the design of supersonic aircraft. A. F. Emsrud.

85 Application of chem-mill to airframe structures. L. G. Hall.

86 The Conway engine. A. A. Lombard.

87 A study of engine characteristics best suited for commercial operation. F. W. Kolk.

88 Molybdenum for aircraft applications. R. T. Begley.

89 Designing materials for future aerial vehicles. N. E. Promisel.

91 Pre-flight development of modern aircraft. H. W. Adams.

92 Trends in modern aircraft structural design. E. H. Spaulding.

93 Effect of hot day performance on jet transport economics. D. W. Finlay.

94 Thrust measurement for jet transport operation. M. J. Saari.

95 Successful containment of high-speed turbine failures. W. W. Houghton and E. R. Phillips.

96 Cruise control instrumentation for turbojet aircraft. H. F. Kidder.

98 Developments in aircraft turbine lubricants. T. F. Davidson and J. H. Way.

99 Turbine-powered aircraft demand new fuel handling techniques. W. S. Little.

101 Visual avoidance of mid-air collisions. W. D. Howell and R. B. Fisher.

104 The ramjet-turbojet propulsion system for supersonic flight. R. T. De Vault.

105 Application of auxiliary power to helicopters. D. S. Chatfield.

106 Engineering design for human limitations. J. D. Caldara.

107 Human factors in the design of high performance aircraft. R. B. Crisman and C. L. Forrest.

109 Accessories for high Mach number engines. J. D. Delano.

110 Automatic flight control systems requirements for high performance fighter aircraft. N. Grossman.

111 Progress in aerial refuelling. P. G. Schloemer.

112 Thrust reversers for jet aircraft. F. J. Stimler and J. F. McDermott.

113 Performance and operational studies of two full-scale jet-engine thrust-reverser systems. R. C. Kohl and J. S. Algranti.

114 Overrun safety arrestment of commercial jet aircraft. C. J. Daniels.

T33 Alloy titanium in the J57 turbojet engine. W. H. Sharp.

## *U.S. Department of Agriculture: Forest Products Laboratory—Reports*

1505 Flexural rigidity of a rectangular strip of sandwich construction. H. W. March and C. B. Smith.

1505A Supplement to the flexural rigidity of a rectangular strip of sandwich construction. C. B. Norris *et al.*

1525 Buckling loads of flat sandwich panels in compression. Various types of edge conditions. H. W. March and C. B. Smith.

1525A Buckling loads of flat sandwich panels in compression. The buckling of flat sandwich panels with edges simply supported. K. H. Boller.

1525D Buckling loads of flat sandwich panels in compression. Buckling of flat sandwich panels with all edges clamped. K. H. Boller.

1525E Buckling loads of flat sandwich panels in compression. The buckling of flat sandwich panels with either all edges simply supported or all edges clamped. K. H. Boller.

1550 Methods for testing and evaluating cargo flooring for transport aircraft. M. P. Brokaw.

1550A Tests of cargo flooring L for aircraft. L. A. Yolton.

1550B Tests of cargo flooring M for aircraft. L. A. Yolton.

1550C Development of a sandwich-type cargo floor for transport aircraft. L. A. Yolton.

1550D Tests of cargo flooring N and P for aircraft. J. A. Liska.

1550E Tests of cargo flooring R and S for aircraft. J. A. Liska.

1550F Tests of cargo flooring Nn and T for aircraft. J. A. Liska.

1550G Tests of cargo flooring Pp and U for aircraft. L. F. Johnson.

1550H Summary of the results of tests of cargo flooring for aircraft (A through U). L. F. Johnson and J. A. Liska.

1550I Tests of extruded magnesium cargo flooring for aircraft. J. A. Liska.

1558 Design criteria for long curved panels of sandwich construction in axial compression. E. W. Kuenzi.

1559B Fatigue of sandwich constructions for aircraft. Aluminum face and end-grain balsa core sandwich material tested in shear. F. Werren.

1559C Fatigue in sandwich constructions for aircraft. Fiberglas-honeycomb core material with fiberglas-laminate or aluminum facings, tested in shear. F. Werren.

1559D Fatigue of sandwich constructions for aircraft. Fiberglas-laminate face and end-grain balsa core sandwich material tested in shear. F. Werren.

1559E Fatigue of sandwich constructions for aircraft. Cellular-hard-rubber core material with aluminum or fiberglas-laminate facings, tested in shear. F. Werren.

1559H Fatigue of sandwich constructions for aircraft. (Aluminum facing and aluminum honeycomb core sandwich material tested in shear.) F. Werren.

1559I Fatigue of sandwich constructions for aircraft. (Glass-fabric-laminate facing and waffle-type core sandwich material tested in shear.) F. Werren.

1559J Fatigue of sandwich constructions for aircraft. (Glass-fabric-laminate facing and alkyd Isocyanate foamed-in-place core sandwich material tested in shear.) F. Werren.

1559K Fatigue of sandwich constructions for aircraft. (Aluminum facing and expanded-aluminum-honeycomb core sandwich material tested in shear.) F. Werren.

1560 Shear ability of flat panels of sandwich construction. E. W. Kuenzi and W. S. Ericksen.

1571 Stability of a few curved panels subjected to shear. E. W. Kuenzi.

1573B Durability of low-density core materials and sandwich panels of the aircraft type as determined by laboratory tests and exposure to the weather. B. G. Heebink *et al.*

1573C Durability of low-density sandwich panels of the aircraft type as determined by laboratory tests and exposure to weather. V. C. Setterholm *et al.*

1574 Fabrication of lightweight sandwich panels of the aircraft type. B. G. Heebink *et al.*

1583 Effects of shear deformation in the core of a flat rectangular sandwich panel. 1. Buckling under compressive end load. 2. Deflection under uniform transverse load. H. W. March.

1583A Effects of shear deformation in the core of a flat rectangular sandwich panel. Stiffness of flat panels of sandwich construction subjected to uniformly distributed loads normal to their surfaces—simply supported edges. W. J. Kommers and C. B. Norris.

1583B Effects of shear deformation in the core of a flat rectangular sandwich panel. Compressive buckling of sandwich panels having facings of unequal thickness. W. S. Ericksen and H. W. March.

1583C Supplement to effects of shear deformation in the core of a flat rectangular sandwich panel. Deflection under uniform load of sandwich panels having facings of unequal thickness. W. S. Ericksen.

1583D Supplement to effects of shear deformation in the core of a flat rectangular sandwich panel. Deflection under uniform load of sandwich panels having facings of moderate thickness. W. S. Ericksen.

1584 Repair of aircraft sandwich constructions. E. Panek and B. G. Heebink.

1584A Supplement to repair of aircraft sandwich constructions. A. A. Mohaupt and B. G. Heebink.

1584B Supplement to repair of aircraft sandwich constructions. B. G. Heebink.

1802 Elastic stability of the facings of flat sandwich panels when subjected to combined edgewise stresses. K. H. Boller and C. B. Norris.

1804 Effect of elevated temperatures on the strengths of small specimens of sandwich construction of the aircraft type. E. W. Kuenzi.

1804A Effect of elevated temperatures on the strengths of small specimens of sandwich construction of the aircraft type. (Glass-cloth facings, balsa core—tested immediately after the test temperature was reached.) E. W. Kuenzi.

1804B Effect of elevated temperatures on the strengths of small specimens of sandwich construction of the aircraft type. Tests conducted after exposure to elevated temperatures for 182 hours. E. W. Kuenzi.

1805 Strength properties of plastic honeycomb core materials. W. J. Kommers.

1806 Strength of sandwich constructions subjected to shear at normal temperatures. A. W. Voss and C. B. Norris.

1808 Strength of aluminum lap joints at elevated temperatures. (Tests conducted immediately after the temperature was reached.) E. W. Kuenzi.

D1809A Effect of defects on strength of aircraft-type sandwich panels. A. A. Mohaupt and B. G. Heebink.

R1809 Effect of defects on strength of aircraft-type sandwich panels. B. G. Heebink and A. A. Mohaupt.

1810 Wrinkling of the facings of sandwich construction subjected to edgewise compression. C. B. Norris *et al.*

# Reports

## AERODYNAMICS

### Boundary Layer

*Part I. The effect on transition of isolated surface excrescences in the boundary layer. N. Gregory and W. S. Walker. Part II. Brief flight tests on a Vampire I aircraft to determine the effect of isolated surface pimples on transition. D. Johnson. R. & M.* 2779. (1956).

The effect of isolated surface excrescences in a laminar boundary layer in producing disturbances which may lead to turbulent flow has been examined experimentally by several methods. Photographs of some of the flow patterns visualised by smoke and china-clay techniques are given. The critical heights of pimple which just give rise to spreading wedges of turbulent flow have been measured on a flat plate and on two aerofoils at several angles of incidence. The results are analysed and are presented in a form which enables approximate estimates to be made of the protuberances permissible on laminar-flow surfaces at full-scale flight Reynolds numbers.—(1.1.2.1).

*The numerical integration of the laminar compressible boundary layer equations, with special reference to the position of separation when the wall is cooled. G. E. Gadd. C.P.* 312. (1957).

A method of integrating the laminar compressible boundary layer equations is described. It is assumed that the external velocity at the leading edge of the boundary layer is not zero, but cases with leading edge stagnation points could be dealt with on broadly similar lines. The method enables results of fair accuracy to be obtained even when large intervals of integration are used.—(1.1.1.4 × 1.9.1).

*Effects of probe size on measurements in a laminar boundary layer in supersonic flow. G. R. Ludwig. U.T.I.A. T.N.* 9. (*November* 1956).

A study of probe effects on the laminar boundary layer of a hollow cylinder at a Mach number of 2.50 was made by means of total pressure surveys. Six probes with rectangular tips and one circular probe were used.—(1.1.1.4).

*Stability diagrams for laminar boundary layer flow. R. Timman et al. N.L.L.-T.N. F.* 193.

For a one-parameter family of boundary layer velocity profiles stability diagrams are given. The method of calculation applied starts from the asymptotic behaviour of the inviscid differential equation of disturbance. This method makes use of only one solution in the complete domain of integration.—(1.1.1).

*On the contribution of turbulent boundary layers to the noise inside a fuselage. G. M. Corcos and H. W. Liepmann. N.A.C.A. T.M.* 1420. (*December* 1956).

The concept of attentuation is abandoned and instead the problem is formulated as a sequence of two linear couplings: the turbulent boundary layer fluctuations excite the fuselage skin in lateral vibrations and the skin vibrations induce sound inside the fuselage.—(1.1.3).

*Average properties of compressible laminar boundary layer on flat plate with unsteady flight velocity. F. K. Moore and S. Ostrach. N.A.C.A. T.N.* 3886. (*December* 1956).

The time-average characteristics of boundary layers over either an insulated or isothermal flat plate in nearly quasi-steady flow are determined. Time averages are found without specifying plate velocity explicitly except that it is positive and has an average value. The time average quasi-steady terms are compared to steady flow values at the corresponding average velocity and the effects of the frequency dependent averages are discussed.—(1.1.1.4 × 1.9.1).

*Simplified method for estimating compressible laminar heat transfer with pressure gradient. E. Reshotko. N.A.C.A. T.N.* 3888. (*December* 1956).

An approximation is made in the method of T.N. 3326 which simplifies the calculation of heat transfer. Good agreement with the method of T.N. 3326 is expected for isothermal surfaces with adverse and small favourable pressure gradients regardless of surface temperature and also for flow with large favourable pressure gradient over cooled surfaces.—(1.1.1.4 × 1.9.1).

*Boundary-layer transition at Mach 3·12 as affected by cooling and nose blunting. N. S. Diaconis et al. N.A.C.A. T.N.* 3928. (*January* 1957).

Transition studies were made on a blunted cone-cylinder and parabolic-nosed cylinder at Reynolds numbers per foot up to $8 \times 10^6$—(1.1.2.4 × 1.9.1).

### Compressible Flow

*The displacement effect of Pitot tubes in narrow wakes. G. B. Marson and G. M. Lilley. CoA Report No.* 107. (*October* 1956).

The apparent displacement of the effective centre of a circular Pitot from its geometric centre when placed in narrow wakes has been measured at sub- and supersonic speeds.—(1.2).

*Theory of free-molecule, orifice-type, pressure probes in isentropic and nonisentropic flows. G. N. Patterson. U.T.I.A. Report No.* 41. (*November* 1956).

The theory is presented of a pressure probe in the form of an orifice in the side of a tube which may be orientated in any direction relevant to that of the mass motion and which is so small compared with the local mean free path, that free-molecule flow occurs.—(1.2.3).

*The normal shock wave at hypersonic speeds. Z. O. Bleviss and G. R. Inger. Douglas Report No. S.M.*-22624. (*November* 1956).—(1.2.3.2).

*The calculation of minimum supersonic drag by solution of an equivalent two-dimensional potential problem. E. W. Graham. Douglas Report S.M.*-22666. (*December* 1956).—(1.2.3.1).

*Tables of characteristic functions for solving boundary-value problems of the wave equation with application to supersonic interference. J. N. Nielsen. N.A.C.A. T.N.* 3873. (*February* 1956).

Tables are presented containing 69,000 values of a set of characteristic functions of two variables which first arose in problems of supersonic wing-body interference. The functions solve boundary value problems of the second kind for the wave equation in three dimensions with circular cylindrical boundaries or problems of the unsteady heat conduction equation in two space dimensions with circular boundaries. The functions themselves have the physical significance of cylindrical pressure waves. The tables have extensive use in problems of aerodynamic interference at supersonic speeds.—(1.2.3).

*Wind-tunnel technique for simultaneous simulation of external flow field about nacelle inlet and exit airstreams at supersonic speeds. G. W. Englert and R. W. Luidens. N.A.C.A. T.N.* 3881. (*January* 1957).

An investigation was made of several ways of simultaneously simulating an external pressure field generated by an engine exhaust jet and an air inlet.—(1.2.3).

*Investigation of variation in base pressure over the Reynolds number range in which wake transition occurs for nonlifting bodies of revolution at Mach numbers from 1·62 to 2·62. V. Van Hise. N.A.C.A. T.N.* 3942. (*January* 1957).

Results are presented of the effects of Mach number and Reynolds number upon the base pressure of non-lifting ogival bodies of revolution over the Reynolds number range in which wake transition occurs. The Mach number varied from 1·62 to 2·62 and the overall Reynolds number range was approximately from 20,000 to 10,000,000.—(1.2.3).

NOTE.—*The figures in parenthesis at the end of each Summary are for office use only.*

CONTROL SURFACES—*see also* WINGS AND AEROFOILS

*Low speed tests of an airbrake using low pressure air ejected through spanwise slots. R. S. Trayford. A.R.L. Note F. 25. (August* 1956).

Low speed tests on a 10 per cent aerofoil section using air ejected from spanwise slots, show drag increments large enough for this system to be used as an air-brake.—(1.3.4).

FLUID DYNAMICS

*Free-stream boundaries of turbulent flows. S. Corrsin and A. L. Kistler. N.A.C.A. Report* 1244. (1955).

The instantaneously sharp and irregular front which separates turbulent fluid from contiguous "non-turbulent" fluid at a free-stream boundary is studied. Theoretical analysis is backed up by experimental results.—(1.4.2).

INTERNAL FLOW

*Tests concerning novel designs of blades for axial compressors. S. J. Andrews et al. R. & M.* 2929. (1956).

Two sets of blade designs were investigated. The first set was designed with an increased work input at the root and tip of the blades in order to re-energise the boundary layer and prevent axial-velocity profile deterioration. The second set was designed using as a design assumption a mathematical approximation to the axial-velocity profiles found experimentally at various stages in a conventional compressor.—(1.5.2).

LOADS—*see also* WINGS AND AEROFOILS

*Sidewash in the vicinity of lifting swept wings at supersonic speeds. P. J. Bobbitt and P. J. Maxie. N.A.C.A. T.N.* 3938. (*February* 1957).

Equations and charts have been presented for the conical part of the sidewash above and below swept wings at small angles of attack. This flow-field component is necessary in making calculations of the wing-induced forces and moments on stores, missiles, and pylons. All supersonic Mach numbers and wing leading edge sweep angles have been considered.—(1.6.1 × 1.10.1.2).

*Comparison of calculated and experimental load distributions on thin wings at high subsonic and sonic speeds. J. L. Crigler. N.A.C.A. T.N.* 3941. (*January* 1957).

A method for calculating the aerodynamic loading on a wing in combination with a body is presented. Calculated results are compared with experimentally measured data for two wing-body configurations throughout a range of Mach number up to 1·0.—(1.6.1).

STABILITY AND CONTROL—
*See also* TESTING AND INSTRUMENTS

*The spinning of model aircraft and the prediction of full-scale spin and recovery characteristics. G. E. Pringle and D. J. Harper. R. & M.* 2906. (1956).

Some technical aspects are discussed of a long series of tests made with dynamic scale model aircraft in the Royal Aircraft Establishment Vertical Tunnel for the purpose of studying their spinning characteristics. There is some discussion of the sensitivity of the spinning model to applied forces including those that upset the spin to produce recovery and those that alternatively generate a new spin. The difference between model- and full-scale spins is analysed with a view to correcting the model data, and some attention is given to power-on spins. A chapter is given to special aspects of the spin of tailless aircraft, and another to safety devices.—(1.8.3.1).

*The time vector method for stability investigations. Part I. Basic information. Part II. Longitudinal motion. K. H. Doetsch. R. & M.* 2945. (1957).

A semi-graphical method for dynamic stability analysis is described. It is based on the concept of rotating time vectors which has long been applied to oscillations of constant amplitude. For the more general case of damped or divergent oscillations met with in flight stability, however, some additional rules had first to be established. Part I of the report deals essentially with their derivation.—(1.8.2.1).

*Aerodynamic transfer functions: an improvement on stability derivatives for unsteady flight. B. Etkin. U.T.I.A. Report No.* 42. (*October* 1956).

The classical representation of aerodynamic forces in unsteady flight by means of stability derivatives is theoretically objectionable and may lead to errors of engineering importance. By using the Laplace transform, and the concept of transfer functions, a valid representation is obtained of the aerodynamic forces in the small-perturbation equations of aeroplane dynamics. Aerodynamic transfer functions are defined which may be regarded as generalisations of the classical derivatives, and which may be approximated by them.—(1.8).

*A new standard for the prediction of full scale spin and recovery characteristics for model tests. T. H. Kerr. AGARD Report* 25. (*February* 1956).

The important features of a model, which affect the scale effect in the spin and recovery are discussed in the light of several model to full scale comparisons and the general background of spinning experience.—(1.8.3.1).

*Some results of comparison of model and full-scale spinning tests. A. J. Marx. AGARD Report* 26. (*February* 1956).

Results are presented of comparison of wind tunnel and full-scale spinning tests for the Fokker S-11 primary trainer.—(1.8.3).

*Effects of wing position and vertical-tail configuration on stability and control characteristics of a jet-powered delta-wing vertically rising airplane model. P. M. Lovell and L. P. Parlett. N.A.C.A. T.N.* 3899. (*January* 1957)

The results of a flight- and force-test investigation to determine the effects of wing position and vertical-tail configuration on the stability and control characteristics of a jet-powered delta-wing vertically rising aeroplane model are presented. The model had conventional flap-type controls in addition to jet-reaction controls. The effects of various artificial stabilising devices were determined.—(1.8).

THERMO-AERODYNAMICS—*see also* BOUNDARY LAYER

*Skin temperatures and heat transfer over wedge wings at extreme speeds. T. Nonweiler. CoA Report No.* 105. (*August* 1956).

Formulae and charts are presented to enable the actual skin temperature close to the nose to be predicted, for a wedge-shaped wing, in terms of skin thickness and conductivity.—(1.9.1).

WINGS AND AEROFOILS—*see also* LOADS

*Force and moment measurements on a conical body and a rectangular wing, separately and in combination, at Mach number* 1·94. *J. R. Anderson and D. Treadgold. R. & M.* 2864. (1956).

Results are given of wind tunnel measurements at $M = 1{\cdot}94$ of lift, drag and pitching moment at small angles of incidence on two cones, three rectangular wings and on the six derived cone-wing combinations. A description of the tests and a comparison with theory are also included.—(1.10.2.2).

*Some remarks on Multhopp's subsonic lifting-surface theory. K. W. Mangler and B. F. R. Spencer. R. & M.* 2926. (1956).

An alternative method is given to that proposed by Multhopp in his subsonic lifting-surface theory for dealing with the spanwise integration of the downwash. The method consists of arranging the series form of the influence function near the inducing section so that the logarithmic term may be integrated instead of introducing an artificial correction function as Multhopp does. Multhopp's scheme for the solution of the system of linear equations is retained and there is no increase in the amount of computer work involved.—(1.10.1.2).

*Three-dimensional wind-tunnel tests of a 30° jet flap model. J. Williams and A. J. Alexander. C.P.* 304. (1957).

As a first investigation of finite aspect ratio effects in relation to the jet flap scheme, pressure plotting experiments were made on a small-scale model, with a 12½ per cent thick wing section already tested under two-dimensional conditions at the N.G.T.E.—(1.10.2.2 × 1.3.4).

*Wind tunnel tests on a 6% two-dimensional aerofoil in the transonic speed range. P. E. Turner. A.R.L. Report A.* 99. (*August* 1956).

Pressure distributions, schlieren photographs of the flow near the trailing edge and wake traverse profiles are presented for a modified N.A.C.A. 64-106 aerofoil at zero incidence in the Mach number range 0·5 to 1·04. A comparison is made between results obtained with natural transition and with transition artificially fixed by roughness close to the leading edge.—(1.10.2.1).

*Calculation of aerodynamic forces on slowly oscillating rectangular wings in subsonic flow. A. I. v. d. Vooren and E. M. De Jager. N.L.L.-T.N. F.* 192. (*October* 1956).

A method is presented for the calculation of the aerodynamic forces on a slowly oscillating aerofoil. The method is essentially a lifting surface theory which takes into account the unsteady effects due to the wake. Results are given as series containing terms of increasing powers in reduced frequency. The method has been applied to rectangular aerofoils.—(1.10.1.2 × 1.6.3).

*Curves of lift-to-drag ratios of certain midwing monoplane configurations in supersonic flight. M. E. Graham. Douglas Report No. S.M.*-22640. (*November* 1956).

Curves are presented of lift-drag ratios of certain mid-wing monoplane configurations in supersonic flight. The configuration is essentially a uniformly loaded thin wing (of elliptic plan form and circular arc profiles of same radius) centrally mounted on a "supersonically area-ruled" Sears-Haack fuselage.—(1.10.1.2).

*On the kernel function of the integral equation relating the lift and downwash distributions of oscillating finite wings in subsonic flow. C. E. Watkins et al. N.A.C.A. Report* 1234. (1955).

The kernel function of an integral equation relating the downwash to the lift distribution of a finite wing oscillating in subsonic compressible flow is treated. The kernel is reduced to a form which is amenable to calculations and the types of singularities are shown.—(1.10.1.2 × 1.6.3).

*Theoretical span load distributions and rolling moments for sideslipping wings of arbitrary plan form in incompressible flow. M. J. Queijo. N.A.C.A. Report* 1269. (1956).

A method is presented for determining the span load distribution and rolling moment due to sideslip for wings of arbitrary plan form in incompressible flow. The method was used to prepare charts from which the rolling moment due to sideslip can be obtained for wings having a large variety of aspect ratio, sweep, and taper ratio. Calculated values of span loads and rolling moments are compared with those of other theories and with experimental results.—(1.10.1.2 × 1.6.1).

*Wind-tunnel investigation of jet-augmented flaps on a rectangular wing to high momentum coefficients. V. E. Lockwood et al. N.A.C.A. T.N.* 3865. (*December* 1956).

Results and a discussion are presented of a preliminary investigation of jet flaps made in the 300 m.p.h. 7 by 10-foot tunnel on an unswept, untapered wing with an aspect ratio of 8·4 and a thickness of 16·7 per cent.—(1.10.2.2 × 1.3.4).

*A method for predicting lift increments due to flap deflection at low angles of attack in incompressible flow. J. G. Lowry and E. C. Polhamus. N.A.C.A. T.N.* 3911. (*January* 1957).

A method is presented for estimating the lift due to flap deflection at low angles of attack in incompressible flow. In this method provision is made for the use of incremental section-lift data for estimating the effectiveness of high lift flaps. The method is applicable to swept wings of any aspect ratio or taper ratio. Also included is a simplified method of estimating the lift-curve slope throughout the subsonic speed range.—(1.10.1.2 × 1.3.4).

*Effect of propeller location and flap deflection on the aerodynamic characteristics of a wing-propeller combination for angles of attack from 0° to 80°. W. A. Newsom. N.A.C.A. T.N.* 3917. (*January* 1957).

The investigation was conducted with a model having four propellers, the slipstream from which covered practically the entire span of the wing. The wing had a 30 per cent chord slotted flap and an 8·5 per cent chord slat. The tests covered two longitudinal and two vertical positions of the propeller relative to the wing, and a range of flap deflections, with slat off and slat on.—(1.10.2.2 × 1.3.4).

*Investigation of effectiveness of a wing equipped with a 50-percent-chord sliding flap, a 30-percent-chord slotted flap, and a 30-percent-chord slat in deflecting propeller slipstreams downward for vertical take-off. R. E. Kuhn. N.A.C.A. T.N.* 3919. (*January* 1957).

Results are presented of an investigation of the effectiveness of a wing equipped with a 50 per cent chord sliding flap and a 30 per cent chord slotted flap in deflecting a propeller slipstream downward for vertical take-off.—(1.10.2.2 × 1.3.4).

## Helicopter Aerodynamics

*Second harmonic control on the helicopter rotor. W. Stewart. R. & M.* 2997. (1957).

The application of second harmonic control on a helicopter rotor causes a redistribution of the loading over the disc. This can be utilised to postpone the forward speed limitations imposed by stalling of the retreating blade. This report develops the theory for second harmonic control. The resultant flapping motion and subsequent incidence distribution depend mainly on blade inertia number. A practical check on the flapping with a full-scale rotor on a testing tower gave excellent agreement with the theory.—(1.11.3).

*Theory of self-excited mechanical oscillations of helicopter rotors with hinged blades. R. P. Coleman and A. M. Feingold. N.A.C.A. T.N.* 3844. (*February* 1957).

A theoretical analysis for the self-excited mechanical oscillations of hinged rotor blades is described and methods for its application are explained. The theory includes the effects of unequal stiffness of the pylon for deflections in different directions and the effects of damping in the hinges and in the pylon. Both the derivation of the characteristic equation and the methods of application of the theory are given. Charts are presented from which the shaft critical and self-excited instabilities can be predicted for a great variety of cases.—(1.11 × 33.1.2).

*Differential equations of motion for combined flapwise bending, chordwise bending, and torsion of twisted nonuniform rotor blades. J. C. Houbolt and G. W. Brooks. N.A.C.A. T.N.* 3905. (*February* 1957).

The differential equations of motion for the lateral and torsional deformations of twisted rotating beams are developed for application to helicopter rotor and propeller blades. No assumption is made regarding the coincidence of the neutral, elastic, and mass axes, and the generality is such that previous theories involving various simplifications are contained as subcases to the theory developed and presented in this paper. Special attention is given to coupling terms not found in previous theories, and methods of solution of the equations of motion are indicated by selected examples.—(1.11 × 29 × 33.2.4.1.10).

*Approximate solution for streamlines about a lifting rotor having uniform loading and operating in hovering or low-speed vertical-ascent flight conditions. W. Castles. N.A.C.A. T.N.* 3921. (*February* 1956).

A realistic approximation for low-speed flow patterns is obtained by adding the stream functions for the displacement velocity of a disc and a ring source coincident with the rim of the rotor to the stream functions for the uniform vortex cylinder and the free-stream velocity. Equations are derived for the relative strengths of the stream functions that are necessary to satisfy certain selected physical conditions. Tables of values of the composite stream function are given for hovering and three rates of

vertical ascent which cover the helicopter flight range. A method is outlined for using the tabulated values of the stream functions to compute the induced velocity components at any selected locations.—(1.11.3).

*Methods for obtaining desired helicopter stability characteristics and procedures for stability predictions.* F. B. Gustafson and R. J. Tapscott. *N.A.C.A. T.N.* 3945. (*February* 1957).

Part I summarises the methods available to the helicopter designer for obtaining desired stability characteristics by modifications to the airframe design. The discussion is based on modifications made during establishment of flying-qualities criteria and includes sample results of theoretical studies of additional methods. In Part II some of the methods of predicting rotor stability derivatives have been reviewed and the methods by which the derivatives are employed to estimate stability characteristics are summarised.—(1.11.2).

*Instrument flight trials with a helicopter stabilized in attitude about each axis individually.* S. Salmirs and R. J. Tapscott. *N.A.C.A. T.N.* 3947. (*January* 1957).

Pilots' opinions and a simplified statistical analysis of the data were used to evaluate the results of helicopter flight investigations of single-axis attitude stabilisation during low-speed instrument approaches. During calm-air flight, heading stabilisation provided the most favourable results, with pitch stabilisation and roll stabilisation following in that order. Under variable wind conditions, pitch stabilisation provided the most significant contribution.—(1.11.2).

### Testing and Instruments

*The R.A.E. 4-ft. × 3-ft. experimental low-turbulence wind tunnel. Part II. Measurements of turbulence intensity and noise in the working-section.* H. Schuh and K. G. Winter. *R. & M.* 2905. (1957).—(1.12.1.1).

*Technique for flutter tests using ground-launched rockets, with results for unswept wings.* W. G. Molyneux et al. *R. & M.* 2944. (1956).

Model wings are attached to a solid-fuel rocket which has a miniature telemetry set housed in a detachable nose fairing. A vibration pick-up and break wires are fitted in the flutter model and these modulate the output of the telemetry set to transmit flutter information to a ground station. The rocket is fired over an open artillery range and its velocity-time curve is obtained by radio reflection Doppler equipment.—(1.12.2 × 2).

*Development of a transonic slotted working section in the N.A.E. 30-inch × 16-inch wind tunnel.* J. A. Laurmann and J. Lukasiewicz. *N.A.E. L.R.*-178. (*August* 1956).—(1.12.1.2).

*Special applications of strain-gage balances used in the supersonic and hypersonic wind tunnels at the U.S. Naval Ordnance Laboratory.* J. R. Lightfoot and C. E. White. *AGARD Report* 8. (*February* 1956).

The purpose, functional description and operation are described of three types of strain-gauge balances developed at the N.O.L.; the balance for spinning models, the aerodynamic damping balance, and the temperature-controlled balance.—(1.12.4).

*Development of half-model wind tunnel balances.* Staff, High speed Aero. Lab. *N.A.E. AGARD Report* 10. (*February* 1956).

Three designs of half-model, three component balances are described and an account is given of the experience obtained with two of them. In all balances, strain gauge transducers, of the bonded or unbonded type, are used for measurement of forces and moments.—(1.12.4).

*A note on a half-model strain-gauge balance.* N. C. Lambourne. *AGARD Report* 11. (*February* 1956).

A general purpose strain-gauge wall-balance recently constructed at the National Physical Laboratory is described briefly. The equipment is designed for the measurement of four components, *viz.* normal force, longitudinal force, pitching moment and rolling moment on half models.—(1.12.4).

*Problems involved in precision measurements with resistance strain gages.* K. H. McFarland and J. Dimeff. *AGARD Report* 12. (*February* 1956).

The electrical, thermal, and mechanical errors which may effect the accuracy of resistance wire strain-gauge measurements are surveyed. The methods currently used to correct for these errors are described briefly in order to increase the accuracy and reproducibility of measuring systems using these gauges as sensing elements.—(1.12.6.2 × 33.3.2).

*Evaluation and calibration of wire-strain-gage wind tunnel balances under load.* R. M. Hausen. *AGARD Report* 13. (*February* 1956).

The way in which loads are applied to strain-gauge balances in the laboratory are discussed and the resulting data is reduced to a convenient form.—(1.12.4).

*"Dead stick" landing testing techniques.* A. R. Holcombe. *AGARD Report* 28. (*February* 1956).

Information gained during United States Navy experiments with dead-stick landings on ten different jet aircraft is presented. Testing methods, glide range determination and landing techniques are discussed.—(1.12.2).

*Flight investigation of a roll-stabilized missile configuration at varying angles of attack at Mach numbers between 0·8 and 1·79.* J. Zarovsky and R. A. Gardiner. *N.A.C.A. T.N.* 3915. (*January* 1957).

A missile research model was flown at supersonic speed to determine the quality of automatic roll stabilisation at varying angles of attack. Aerodynamic rolling and pitching derivatives were determined from the flight record. It was concluded that the combination of the gyro-actuated automatic pilot with wing-tip ailerons provided adequate roll stabilisation under conditions encountered in flight.—(1.12.2 × 1.8 × 25.2)

## AEROELASTICITY

*See also* Testing and Instruments

*The theoretical determination of normal modes and frequencies of vibration.* I. T. Minhinnick. *AGARD Report* 36. (*April* 1956).

The various methods that have been devised for the determination of the natural frequencies and normal modes of aircraft are discussed and their accuracy and the amount of work that they entail are compared. An extensive bibliography is given. The discussion is mainly from the point of view of the flutter analyst, who commonly bases his analyses on the normal modes, but the description and comparison of the various methods should be of general interest.—(2).

## DESIGN AND CONSTRUCTION

*Some advantages and disadvantages of variable and non-linear gearing between the pilot's control and the control surface.* D. A. Lang. *C.P.* 263. (1956).

The advantages and disadvantages arising from the use of variable and non-linear gearing are considered, mainly in relation to a reduction of the pilot's control movements required during an approach under bumpy conditions, to reducing over-sensitivity of control at high speed and mitigating the effects of friction and backlash.—(4.2.3).

## AIRCRAFT OPERATION

*Ditching investigations of dynamic models and effects of design parameters on ditching characteristics.* L. F. Fisher and E. L. Hoffman. *N.A.C.A. T.N.* 3946. (*February* 1957).

Data from ditching investigations conducted at the Langley Aeronautical Laboratory with dynamic scale models of various aeroplanes are presented in the form of tables. The effects of design parameters on the ditching characteristics of aeroplanes, based on scale-model investigations and on reports of full-scale ditchings, are discussed. Various ditching aids are also discussed as a means of improving ditching behaviour.—(5.3).

## HYDRODYNAMICS

*Impact-loads investigation of chine-immersed models having concave-convex transverse shape and straight or curved keel lines.* P. M. Edge. *N.A.C.A. T.N.* 3940. (*February* 1957).

Hydrodynamic loads data obtained at the Langley impact

basin from impacts of a concave-convex transversely curved bottom mounted on narrow beam models having straight keel, curved bow, and curved stern are presented. Impacts were made at fixed trim angles over a range of landing conditions, including a few rough water landings. The data are analysed to show the effects of transverse curvature, longitudinal curvature, and rough water on maximum impact loads for narrow beam models tested.—(17 × 33.1).

## MATERIALS

*See also* STRUCTURES—THEORY AND ANALYSIS

*Comparison of mechanical properties of flat sheets, molded shapes, and postformed shapes of cotton-fabric phenolic laminates. F. W. Reinhart et al. N.A.C.A. T.N.* 3825. (*January* 1957).

Tests were conducted to determine the properties of flat sheets, moulded shapes, and post-formed shapes of cotton-fabric phenolic laminates. Most of the sheet materials showed directional variations in strength. The effects of industrial and laboratory post-forming and moulding were compared.—(21.3).

*Investigation of the NiAl phase of nickel-aluminum alloys. E. M. Grala. N.A.C.A. T.N.* 3828. (*January* 1957).

An investigation was made to determine the effects of composition and homogenisation heat treatments on the hardness and tensile properties of cast alloys of the NiAl intermetallic phase. This phase exists over a wide range of composition (approximately 24 to 37 weight per cent aluminium at 500°C) with stoichiometric NiAl at 31·5 per cent aluminium. Relatively small changes in composition within the NiAl phase resulted in appreciable hardness and strength changes.—(21.2).

## MATHEMATICS

*Singular perturbations; a model equation. H. C. Levey. A.R.L. Note A.* 157. (*January* 1957).

The class of singular perturbation problems is defined in general terms. The equation $\alpha(dy/dx)+xy=1$ provides a simple example showing two main features of singular perturbation behaviour, namely, the boundary layer and the shock discontinuity.—(22).

## MISSILES

*See* TESTING AND INSTRUMENTS

## POWER PLANTS

*Free-jet tests of a 1·1-inch-diameter supersonic ram-jet engine. J. H. Judd and O. F. Trout. N.A.C.A. T.N.* 3906. (*February* 1957).

Results are presented of free-jet tests of a 1·1 inch diameter hydrogen-burning ram-jet engine over a Mach number range from 1·42 to 2·28 and a Reynolds number range from $6{\cdot}01 \times 10^6$ to $15{\cdot}78 \times 10^6$.—(27.4).

## PROPELLERS

*See* HELICOPTER AERODYNAMICS

## FATIGUE

*Effects of cyclic stress and frequency on deformation markings in fatigued copper. D. S. Kemsley. A.R.L. Report Met.* 17. (*August* 1956).

Fatigue deformation markings (striations) produced by cyclic stressing may be revealed both on the surface and in the interior of specimens by suitable etching. Fractured rotating-cantilever specimens tested at stresses ranging from ±10,000 p.s.i. to ±25,000 p.s.i., and frequencies of 21 and 6,000 c.p.m., were sectioned and examined, after polishing and etching, by optical and electron microscopy.—(31.2.2.5).

*The fatigue strength at fluctuating tension ($R=0{\cdot}1$) of Redux bonded 75 S-T clad simple lap joints from −45°C to +80°C. A. Hartman and F. A. Jacobs. N.L.L.-T.N. M.* 2016. (*August* 1956).

Fatigue tests in fluctuating tension, $R=0{\cdot}1$, have been conducted on clad 75 S-T simple lap joints at −45, 20, 50 and 80°C to determine the influence of the temperature on the fatigue strength of Redux bonded joints. The adhesive was cured half an hour at 145 or at 160°C.—(31.2.3.2.4).

*Statistical handling of fatigue data and planning of small test series. W. Weibull. F.F.A. Report* 69. (1957).

General regression formulae are adapted for the purpose of evaluating data from fatigue test series. The concept of linear regression imposes certain particular conditions on the choice of co-ordinates which are stated and analysed. Formulae for computation of the parameters, including the variance in fatigue strength, are derived. The variances in the parameters are deduced for the purpose of setting fiducial limits. The influence of test numbers on the accuracy of the results, and the best apportionment of tests among the stress levels are discussed.—(31.2.1.1.1 × 31.2.1.2).

*Effect of frequency and temperature on fatigue of metals. S. R. Valluri. N.A.C.A. T.N.* 3972. (*February* 1957).

Phenomenological considerations applied to a standard linear solid physical model indicated that for particular temperatures there are corresponding frequencies of fatrgue behaviour changes. It is suggested that at room temperature the critical frequency is above that usually encountered in engineering practice.—(31.1).

## STRUCTURES

LOADS—*see also* HELICOPTER AERODYNAMICS
HYDRODYNAMICS

*Determination of the structural damping coefficients of six full-scale helicopter rotor blades of different materials and methods of construction. F. W. Gibson. N.A.C.A. T.N.* 3862. (*December* 1956).

Results of an experimental investigation of the structural damping of six full-scale helicopter rotor blades, made to determine the variation of structural damping with materials and methods of construction, are presented. The damping of the blades was determined for the first three flapwise bending modes, first chordwise bending mode, and first torsion mode. The contribution of structural damping to the total damping of the blades is discussed for several aerodynamic conditions in order to point out situations where structural damping is significant.—(33.1.2).

*Vertical force-deflection characteristics of a pair of 56-inch-diameter aircraft tires from static and drop tests with and without prerotation. R. F. Smiley and W. B. Horne. N.A.C.A. T.N.* 3909. (*February* 1957).

The vertical force deflection characteristics were experimentally determined for a pair of 56 inch diameter tyres under static and drop-test conditions with and without pre-rotation. For increasing force, the tyres were found to be least stiff for static tests, almost the same as for the static case for pre-rotation drop tests as long as the tyres remain rotating, and appreciably stiffer for drop tests without pre-rotation.—(33.1.2).

THEORY AND ANALYSIS—*see also* HELICOPTER AERODYNAMICS

*Certain methods of stress-analysis of rectangular multi-web box beams. K. H. Griffin. CoA Report No.* 108. (*December* 1956)

The stress distribution in an unswept multi-web box under shear load applied at the centre of a rigid tip rib is examined, and compared with results obtained by a method which replaces the shear webs by a shear-carrying continuum. For the case considered the agreement between the results from the two methods is satisfactory for boxes whose geometry is typical of normal practice. A method of performing root constraint calculations on such a box is outlined and results of an elementary analysis of this type are compared with experiment.—(33.2.4.1.4).

*The torsional rigidity of solid cylinders of double-wedge section. E. H. Mansfield. R. & M.* 2959. (1956).

The torsional rigidity of solid cylinders of double-wedge section is considered theoretically. Minimum energy methods are used to determine close upper and lower limits to the rigidity. The results are presented in graphical form.—(33.2.4.3.4).